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Parametric Estimation of Load for Air Force Datacenters

Derek P. Molle

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PARAMETRIC ESTIMATION OF LOAD FOR AIR FORCE DATA CENTERS

Derek P. Molle, Civ, USAF

AFIT-ENV-MS-15-M-170

**DEPARTMENT OF THE AIR FORCE
AIR UNIVERSITY**

AIR FORCE INSTITUTE OF TECHNOLOGY

Wright-Patterson Air Force Base, Ohio

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PARAMETRIC ESTIMATION OF LOAD FOR AIR FORCE DATA CENTERS
THESIS

Presented to the Faculty
Department of Systems Engineering and Management
Graduate School of Engineering and Management
Air Force Institute of Technology
Air University
Air Education and Training Command
In Partial Fulfillment of the Requirements for the
Degree of Master of Science in Systems Engineering

Derek P. Molle, BS
Civ, USAF

March 2015

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PARAMETRIC ESTIMATION OF LOAD FOR AIR FORCE DATA CENTERS

Derek P. Molle, BS

Civ, USAF

Approved:

John M. Colombi, Ph.D. (Chairman)

John J Elshaw, Ph.D. (Member)

LtCol Brent Langhals, USAF, Ph.D. (Member)

Abstract

The Office of Management and Budget (OMB) has tasked Federal agencies to develop a Data Center Consolidation Plan. Effective planning requires a repeatable method to effectively and efficiently size Air Force Base-level data centers. Review of commercial literature on data center design found emphasis in power efficiency, thermal modeling and cooling, and network speed and availability. The topic of sizing data center processing capacity seems undeveloped. This thesis provides a better, pedigreed solution to the data center sizing problem. By analogy, Erlang's formulae for the probability of blocking and queuing should be applicable to cumulative CPU utilization in a data center. Using survey data collected by 38th Engineering Squadron, a simulation is built and correlation between the observed survey measurements and simulation measurements, and the Erlang, Gamma, and Gaussian-Normal distributions is found.

For a sample dataset of 70 servers over 14 hours of observation and a supposed 0.99999 requirement for traffic to be passed or otherwise unimpeded, Erlang distribution predicts 10 CPU cores are required, Gamma distribution predicts 10 CPU cores are required, Gaussian-Normal distribution predicts 9 CPU cores are required, Erlang B formulae predicts 14 CPU cores are required, and Erlang C formulae predicts 15 CPU cores are required.

Acknowledgments

I would like to thank Dr. John M. Colombi, my faculty advisor, for his guidance, support, and seemingly endless patience throughout the course of this thesis effort. I also need to thank Dr. Brent T. Langhals and Dr. John J Elshaw for their advice regarding various improvements to the text.

Derek Molle

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PARAMETRIC ESTIMATION OF LOAD FOR AIR FORCE DATA CENTERS

I. Introduction

General Issue

From the 1950's through the 1970's, the mainframe data center was the only effective means of computing. Starting in the 1980's and until recently, the cost of individual computing has continued to drop. An overabundance of isolated functional and program managed data centers emerged. Recently, there has been a trend towards consolidation of these data centers to gain economies in staffing, power, environmental control, reliability, and computing power. This is due in large part to advances in high-speed networking technology and processor virtualization, which allow for sharing of processing across a pool of hardware computing resources. Sizing this pool of computing resources remains a challenge and is the focus of this thesis.

Federal mandates through the Federal Data Center Consolidation Initiative (FDCCI) require a 75% reduction in data centers across all federal departments by FY15. Specific to the Department of Defense (DoD), a 40% reduction is expected, which equates to reducing from 772 data centers to 428. DoD Core Data Center (CDC) initiatives have a target objective date of FY18. The discrepancy between the FDCCI and CDC timelines is best explained by the complexity and cost involved in data center consolidation [1].

The Office of Management and Budget (OMB) has tasked Federal agencies to develop a Data Center Consolidation (DCC) Plan in support of FDCCI [2]; a Presidential Directive memo was later issued reinforcing this task [3]. To accomplish this, the

Department of Defense is virtualizing all servers with few exceptions. The preferred approach is using “cloud” technologies, which is a “model for enabling ubiquitous, convenient, on-demand network access to a shared pool of configurable computing resources” [4]. The issue is the cloud needed to house all these virtual servers has not yet been built, designed, or sized.

Problem Statement

One problem that arises in data center consolidation is the sizing of a cloud's virtual environment – effectively, determining the number of central processing units (CPUs). Sizing is accomplished by determining the load, which are time requests from virtual machines for CPUs. The duration of these requests is a random variable, related to the myriad of enterprise applications being used. Load is then derived from the probability distribution for the number of CPU resources occupied simultaneously. Using this probability distribution, the optimal size for a data center virtual environment can be found that minimizes waste (idle CPUs) while avoiding shortages (no free CPUs when requested).

One organization that is providing base data center consolidation support is the Air Force Space Command's (AFSPC) 38th Engineering Squadron, Tinker AFB, OK. When tasked with sizing new data centers, a group there found there was no published formulae or models that could be used to meet the task. Initially the team looked at sizing new requirements based on existing average CPU utilization and scaling that against 60 percent of capacity of the cumulative environment. The 38th design team established 60 percent as a reasonable buffer against peaks in traffic on a basis of

experience with data center applications. They believed this would provide a sufficient margin to account for any transient peaks in processing requirements. This thesis provides a better, pedigreed solution to the data center sizing problem.

Research Focus and Investigative Questions

Spurred by the major initiatives of the Department of Defense to consolidate data centers in support of the Federal Data Center Consolidation Initiative legislated by Congress, this thesis answers the following:

How should the Air Force size physical processing of a proposed data center?

It is important that the new data centers, the new cloud, be designed and sized to support the existing applications that are already fielded. It is also necessary to be able to project and compare costs of varying cloud implementations, such as Infrastructure as a Service (IaaS). Infrastructure as a Service would assume that DoD would outsource the operation, ownership and maintenance of all computing infrastructure and equipment of the data center. Effectively, DoD would pay a service provider on a per-use basis.

An analogy is hypothesized between the Erlang distribution describing the load of human callers in a telephony system and of virtual machines (hosts) requesting CPU time from a Hypervisor. The Erlang distribution is a continuous probability distribution related to other parametric exponential and Gamma distributions. While used originally by A.K. Erlang to estimate the number of phone calls made to a telephone switch, it has general applicability to many traffic engineering and queuing problems. This thesis will validate the use of the Erlang distributions by applying the same general methodology used to historically size telephony systems to size data center virtual environments. To

answer the overall research question, a few investigative questions must first be posed and answered.

1. What are the prevalent metrics for computer processing emphasized by current practice, or found in the academic body of knowledge?
2. How well does an Erlang distribution approximate data center CPU load?
3. How should processing in data centers or IaaS projects be sized?

Methodology

To attempt to answer these investigative questions a review of the technology involved is conducted followed by statistical analysis of measurements taken by a 38th CEIG survey team as well as analysis of a simulation based upon measurements taken during that survey. Correlation between the observed survey measurements, as well as simulation measurements, and the Erlang, Gamma, and Gaussian-Normal distributions will be calculated to test the validity of the proposed sizing solution.

Assumptions/Limitations

Limitations influencing this study include the cost and complexity of testing on a production network, the critical nature of the enterprise data center systems, and the limits of our ability to measure load and generate perfectly realistic traffic. This thesis will assume that Windows® Performance Monitor can provide accurate measurements of load, the open source tool LookBusy can generate realistic traffic, and that these results from a prototype lab running Windows® Hyper-V are sufficiently typical for all hypervisors [5]. This thesis will also assume that the survey data, upon which analysis is based, is typical of an Air Force data center.

Implications

Federal mandates through the Federal Data Center Consolidation Initiative (FDCCI) require a 75% reduction in federal data centers by FY15, with DoD expecting a 40% reduction. The discrepancy between the FDCCI and CDC timelines is best explained by the complexity and cost involved in data center consolidation. The Office of Management and Budget (OMB) has tasked Federal agencies to develop a Data Center Consolidation (DCC) Plan in support of FDCCI. This thesis will provide a repeatable method to effectively and efficiently size base-level data centers.

Preview

In the next chapter background information on data centers, virtualization, metrics for data centers, and some tools for statistical analysis will be introduced. In subsequent chapters, a methodology for statistical analysis of survey results and for simulation of the survey data in a virtual environment, then results from one such survey and analysis of those results as well as analysis of simulation results based upon the survey.

II. Literature Review

Chapter Overview

The purpose of this chapter is to overview technologies, metrics, and statistical analysis tools to provide a background for the thesis question.

Technology

History of Technology

The electronic computer has evolved over the years. The industry started with mainframe computers for laboratories and large firms in the 1940s. In the 1960s the integrated circuit led to the development of the minicomputer and later the microprocessor enabled the personal computer. In the 1969s the ARPANET was established beginning the era of the networked computer [6]. It was in the 1970s that virtualization began in earnest with the development of time-share computing on mainframe computers. Virtualization is defined as a technology which “enables several operating systems and applications to run on one physical server or ‘host.’ Each self-contained virtual machine (VM) is isolated from the others, and uses as much of the host’s computing resources as it requires. [7]”

Virtualization Technology

As time-share computing was further developed modern virtualization technology emerged. It is implemented using a supervisory program referred to as a hypervisor virtual machine manager. The hypervisor abstracts the hardware and presents common interfaces to virtual machines. By sharing common storage it becomes possible for the

virtual machines to almost instantly be migrated, over the network, between physical computers [8].

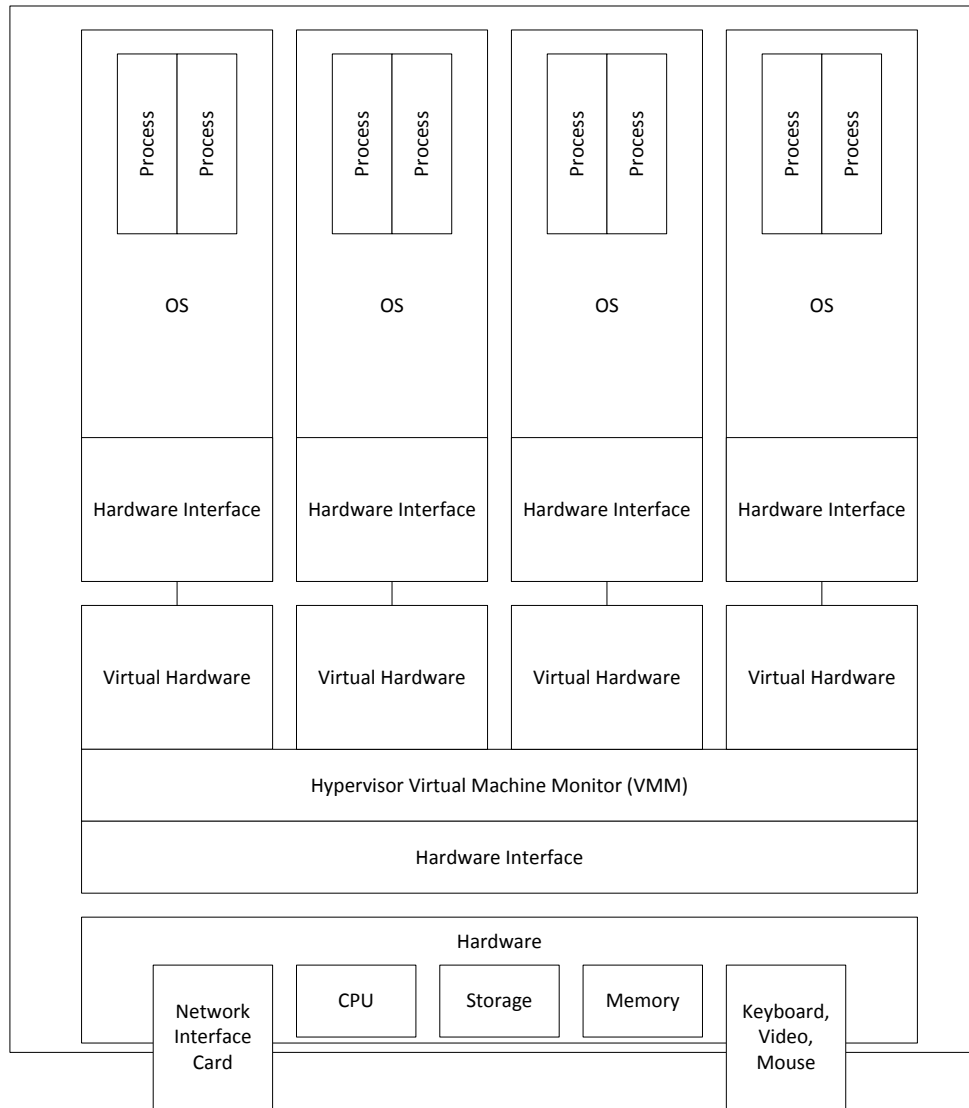


Figure 1. Hardware Abstraction by the Hypervisor

Migration is used to balance load across hosts and to prevent loss of service when hardware goes into maintenance or fails. This creates a common pool of resources across a common network of computers. Policies for management of resources in this common pool are addressed Grit and Wood in "Virtual machine hosting for networked clusters:

Building the foundations for "autonomic" orchestration," and "Black-box and gray-box strategies for virtual machine migration," [9] [10]. Microsoft's Performance and Resource Optimization (PRO) feature for Hyper-V Virtual Machine Manager (VMM) allows administrators to configure target utilization for host hardware in virtual environments. In VMM 2008 the default target CPU utilization is 90 percent [11]. While some details of implementation differ between hypervisors, and there are performance differences between hypervisors, these features are common across all modern hypervisors [5]. The cumulative effect of these features underpinning virtualization is that a small set of hardware can run what used to require a large set of hardware while at the same time offering higher redundancy than before. Below, figures 2 and 4 help illustrate these architectural advantages of virtualization.

Data Center Technology

For the purposes of this paper, the central technological aspect of the data center is the ability to process and store data. This capability is often expressed in terms of Higher Performance Computer (HPC) systems. Hussain and Malik identify three types of HPC architecture: Cluster, Grid, Cloud. The HPC cluster is a group of computers with redundant interconnections that form a highly available system [12]. The cluster is centrally managed and interconnected across a LAN environment. One example would be a website that is load-balanced across multiple web servers in a data center. Frequently the load balancing is accomplished by sharing an IP address across the cluster. The load balancing function is sometimes performed by the cluster itself.

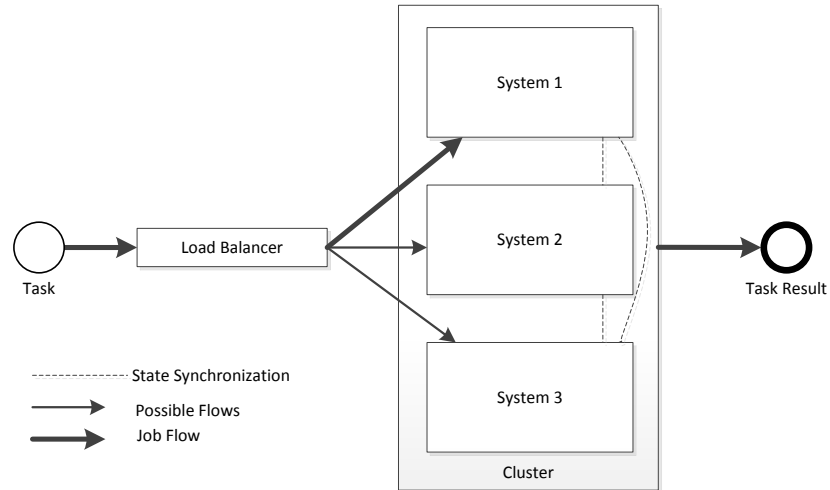


Figure 2. Simple HPC Cluster Architecture

The HPC Grid is a group of computers that use the Internet to spread calculations out across low cost commodity components. A grid does not exist in a single data center but instead in across multiple data centers and frequently homes, classrooms, and office floors where it can use spare compute to complete calculations for the grid. The distributed nature of the grid limits the workload it can take on. Typically grid computing is used to handle non-interactive workloads that can be broken into self-contained chunks to be processed by grid members. The same chunk may be sent to multiple grid members for result verification or to mitigate against the loss of a grid member.

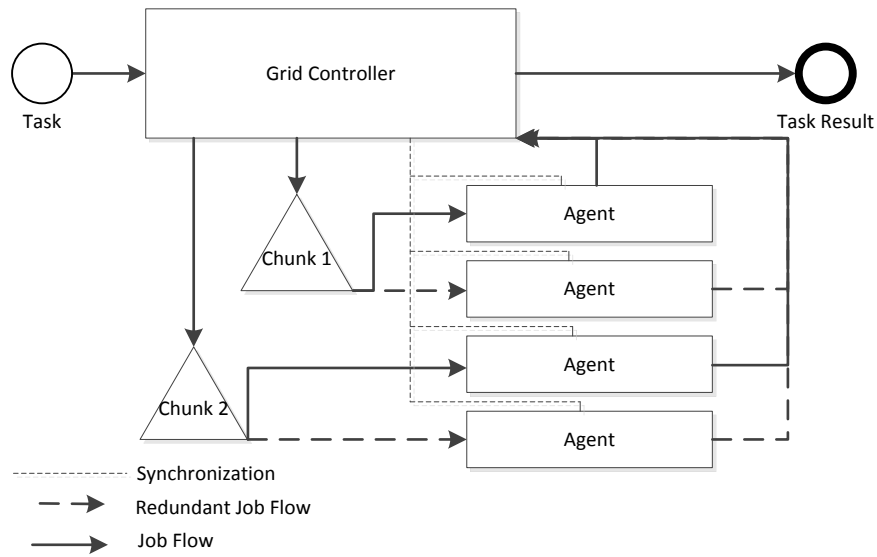


Figure 3. Simple HPC Grid Architecture

HPC cloud computing is an amalgamation of grid and cluster computing. The cloud can exist in a single data center or across data centers, under a single administrative domain or across many, as a private commodity or as a public service.

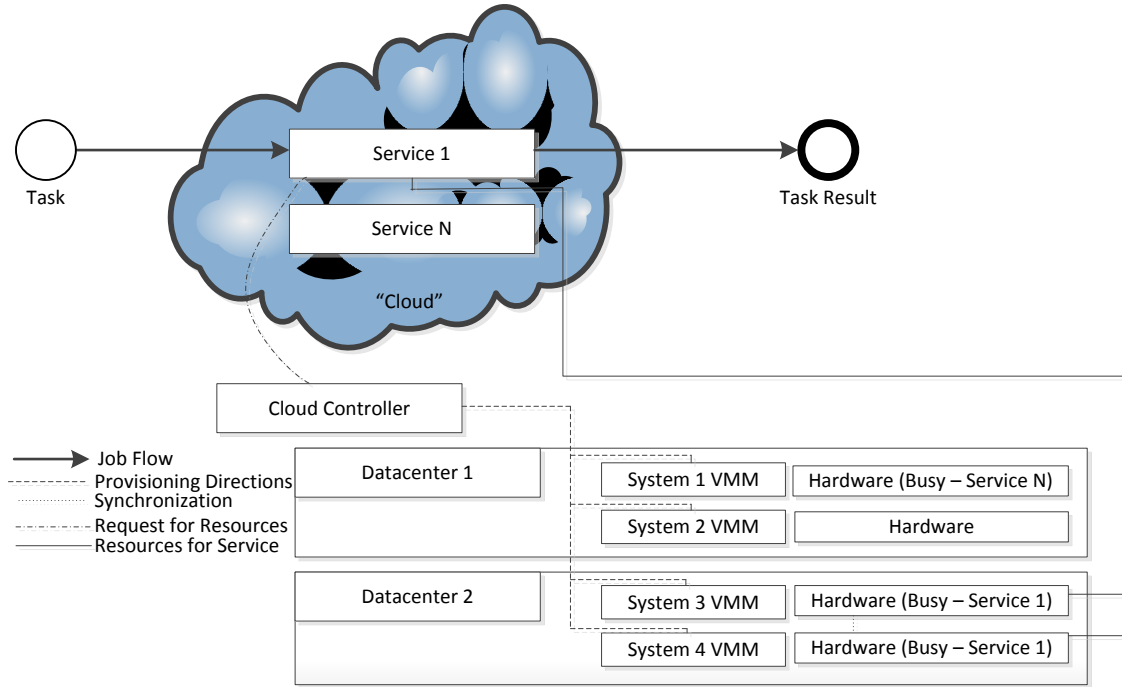


Figure 4. Simple HPC Cloud Architecture

The HPC Cloud architecture is shown in Figure 4. Users are presented with persistent service while the workload is shared across physical data center resources. The system VMM controls scheduling of resources on each system. The single most unique feature of the cloud computing model is that it is entirely virtualized. Where computers participating in a HPC cluster or HPC grid can be virtualized they can also run on bare metal. The self-service and elasticity characteristics of cloud computing requires a common pool of resources to exist in the data center that can be provisioned on request.

Metrics

Traditional Data Center Metrics – Power, Ping, and Pipe

Review of the literature finds remarkably little by the way of similar or alternative solutions to the problem of sizing a data center's compute environment. Instead there is a

great emphasis by recent authors on the "power, ping, and pipe" [13] associated with data center design. Other work describes the goals of "power and pipe" in terms of high power usage effectiveness, PUE, as achieved through efficient power distribution and cooling systems. Methods for achieving "Ping," referring to the need for a responsive and resilient internetwork in the data center, have been well discussed in other work [14] [15] [16] [17].

Load Testing Metrics

There is an existing body of knowledge on the use of software load generators and the analysis and identification of important performance counters. Methods vary from emulation of production networks, stress testing of individual web applications, to arbitrary load generation in commercial cloud environments such as the Amazon Elastic Cloud. [18] [19] [20] [21] [22].

Data Center Metrics

In order to study data center capacity and utilization it is necessary to establish metrics and collection methods. In studying a 1500 node HPC cluster [23] identified SNMP counters, Sampled Flow, and Deep Packet Inspection methods to measure traffic patterns and performance. These are network focused metrics. SNMP is capable of measuring CPU information but it is not implemented in USAF Windows Server deployments. Instead, performance counters and WMI are available to provide reliable information about CPU utilization. Metrics are measured over the interval between two measurement instants [24].

Tools for Statistical Analysis

This section will develop and introduce concepts of statistical analysis by way of descriptive statistics including terms involved in calculations and distributions used by inferential statistics. The purpose of descriptive statistics is to describe and summarize the characteristics of a sample. To accomplish that, measures of mean, median, standard deviation and variance are used. These measures can then be applied to distributions to infer properties of the underlying system. To describe how well a statistical distribution fits a sample dataset the correlation coefficient can be calculated by equation 1.

$$\frac{\sum_{i=1}^n (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^n (x_i - \bar{x})^2 \sum_{i=1}^n (y_i - \bar{y})^2}}$$

Eq. 1

where:

$Correl(X,Y)$ = the correlation coefficient of sets X and Y

x = Sample of X

\bar{x} = Mean of X

y = Sample of Y

\bar{y} = Mean of Y

The Central Limit Theorem is a theory that states, convolution of a sufficiently large number of independent random variables will be approximately normally distributed. This distribution is also referred to as the Gaussian-Normal distribution and shown as equation 2.

$$P(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-(x-\mu)^2/2\sigma^2} \quad \text{Eq. 2}$$

where:

$P_{(x)}$ = Probability Density Function of Gaussian-Normal Distribution
 x = Sample value
 μ = Mean
 σ = Standard Deviation

The Gaussian-Normal distribution is one of the simplest random function used for time-series modeling allowing direct calculation from just mean and standard deviation [25].

Erlang's Formula

This section will develop and introduce Erlang's formulas. The Erlang function is an equation initially published as a solution to telephony problems in *Elektroteknikeren* Vol 13 (1917) by Agner Krarup Erlang [26]. It is founded in the theory of "statistical equilibrium" by which, for a very large number of calls the individual characteristics of each call does not affect the group characteristic as an increase in one call duration will be balanced by a decrease in some other call duration. Erlang supposes the probability of finding all telephone lines engaged (a blocking condition as described by B) can be approximated by the total number of lines and the average number of calls per time unit (traffic intensity) [27]. These dimensionless units of traffic intensity have come to be known as Erlangs. The blocking probability, P_b , is also known as the Grade of Service.

$$\frac{\frac{A^N}{N!}}{\sum_{n=0}^N \frac{A^n}{n!}}$$

Eq. 3

where:

P_b = Probability a request for service is blocked
 A = Normalized load or mean traffic intensity
 N = Number telephone lines

As an alternative to blocking excess traffic, the Erlang C formula describes the probability that a call is placed on hold and waits for service in a queue. To simplify the mathematics of it, it is assumed that callers will wait indefinitely.

$$\frac{\frac{A^N}{N!}}{\sum_{n=0}^N \frac{A^n}{n!} + \frac{A^N}{N!}}$$

Eq. 4

where:

P_w = Probability a call has to wait and is buffered
 A = Normalized load or mean traffic intensity = call frequency x call duration
 N = Number of telephone lines

Under certain conditions P_w can be calculated from P_b , N , and A without an additional round of summation. Where $N > A$ then

$$\frac{P_b}{1 - P_b}$$

Eq. 5

where:

P_w = Probability a call has to wait and is buffered
 P_b = Probability a request for service is blocked
 A = Normalized load or mean traffic intensity
 N = Number of telephone lines

Erlang's formula for solving certain problems in telephony has been applied to computer networks before. Chromy and Baronak [28] applied Erlang distributions to ATM and IP network traffic. They found success for Erlang B in the case of ATM networks and Erlang C for IP networks, noting that ATM and IP handle delay differently. In their work, the Erlang equations were not modified but the parameters were. Specifically, A was used to describe Link utilization and N to describe Bandwidth.

Table 1 : Chromy and Kavacky's common parameters of synchronous and asynchronous networks

Synchronous Network		Asynchronous Network	
B [%]	Lost calls ratio	B [%]	Loss rate
C	Probability of waiting for service	C	Probability of delay
A [Erl]	Total offered traffic	A [%]	Link utilization
N	Number of channels (links)	N [Mbit/s]	Bandwidth

Bonald and Thomas focused on IP traffic and similarly found the probability that internet traffic (IP traffic) , which should reduce flow rate to avoid buffering, is bounded by the Erlang C formula [29]. Bonald and Thomas, similar to Chromy and Kavacky, identified an explicit performance relationship involving only link capacity (N) and expected demand (A).

Erlang's Distribution

This section will introduce the Erlang Distribution and the Gamma Distribution.

Eq. 6

where:

$f(x; \alpha, \beta)$ = Probability Density Function of Gamma Distribution
 x = Sample Value
 $\alpha = \mu^2 / \sigma^2$ = Distribution Shape
 $\beta = \sigma^2 / \mu$ = Distribution Rate

The Erlang Distribution, equation 7, is a special case of the Gamma Distribution, equation 6, where the shape parameter α is a positive integer. This allows the denominator of the distribution to be calculated by factorial rather than by the Gamma function.

Eq. 7

where:

$f(x; \alpha, \beta)$ = Probability Density Function of Erlang Distribution
 x = Sample Value
 $\alpha = \mu^2 / \sigma^2$ = Distribution Shape, a positive integer
 $\beta = \sigma^2 / \mu$ = Distribution Rate

The NIST published Engineering Statistics Handbook cites the Erlang Distribution as being frequently used in queuing theory applications [25].

Summary

The idea of sharing a common pool of computing resources is not a new one. Old time-share methods have been replaced by virtualization technology which is able to abstract and present tasks to generic hardware in a data center. The HPC data center as a

cloud offers users real-time service, with resources on demand. To answer the investigative questions, quantitative metrics are needed. Review of commercial literature finds emphasis in power efficiency, thermal modeling and cooling, and network speed and availability. The topic of sizing data center processing capacity seems undeveloped. By analogy Erlang's formulae seems adaptable to the problem, however, of all of the reviewed literature only one reference to the applicability of Erlang's methodology to CPUs could be found [30]. Other statistical tools from descriptive and inductive statistical analysis can be used to further analyze.

III. Methodology

Chapter Overview

As discussed earlier, there are significant similarities between the telephony problems of 1917 and the modern virtualized computing environment. The greatest possibility for error lay in the analogy of call frequency and duration to CPU utilization. To validate the adaptation of the Erlang formula to problems of the modern data center a medium sized virtual environment was built containing several virtualized application servers and numerous load generating "client" virtual machines. Performance monitors were used to track average CPU utilization from the perspective of the Guest operating system, as well as the System/Processor Queue Length. Processor Queue Length is proportional to the amount of time threads were awaiting physical compute resources and is typically less than 12 [31]. This emulated data will be processed to fit parameters to for the Erlang formula and distribution, as well as the Gamma and Gaussian-Normal distribution using correlation coefficients.

Erlang Formulae Modified For CPU Loading

Since originally the Erlang formulae were intended for sizing telephone circuits, the definitions for some variables must be modified to fit with a virtual data center environment rather than a telephony environment. Based on work by Chromy and Kavacky the definitions of some variables involved in Erlang's formulae should be modified using Table 2.

Table 2 : Common parameters of synchronous Telephony and Virtual Data Center

Telephony		Virtual Data Center	
P_b [%]	Lost calls ratio	P_b [%]	Loss rate
P_w	Probability of waiting for service	P_c	Probability of delay
A [Erl]	Total offered traffic	A [%]	Mean CPU utilization
N	Number of channels (links)	N	Number of logical CPU (cores)

Applying the modified parameters from table 2 to equation 3 and 4 results in equations 8 and 9 below.

$$\frac{P_b}{1 - P_b} = \frac{A}{N - A} \quad \text{Eq. 8}$$

where:

P_b = Probability a request for service is blocked
 A = % Mean CPU Utilization
 N = Number of logical CPU available to the hypervisor

$$\frac{P_c}{1 - P_c} = \frac{A}{N - A} \quad \text{Eq. 9}$$

where:

P_c = Probability a request for service has to wait and is buffered
 A = % Mean CPU Utilization
 N = Number of logical CPU available to the hypervisor

Equations associated with distributions (Eq. 2, 6, 7) are also modified such that $x = N$ and $\mu = A$ therefore $\alpha = A^2 / \sigma^2$ and $\beta = \sigma^2 / A$. The CDF of the Gaussian-Normal, Gamma and Erlang distributions is produced by equation 10.

$$\text{Eq. 10}$$

where:

$f(x)$ = Cumulative Distribution Function

$P(x)$ = Probability Density Function

In practice, all of these functions are calculated by Excel.

Survey Data Collection

When tasked with sizing new data centers as part of a data center consolidation effort, a group at 38th Engineering Squadron, Tinker AFB, OK sent engineering teams to survey the existing Air Force data center infrastructure at prospective sites. Over the course of several days NIPRNET connected systems were identified, the system owners identified and interviewed, and performance information was collected using Windows Performance Monitor from the production application servers. Twenty-seven CPU Utilization samples were taken in 30 minute intervals over the course of 14 hours for each of 70 identified application servers beginning at 10 am. Metrics are measured over the interval between two measurement instants [24]. An example of the survey data is shown in table 3. To protect the OPSEC of the servers their names have been replaced with numbers. This CPU Utilization information, included in Appendix B, is used to generate scripts for simulation of the consolidated data center and for direct statistical analysis in Chapter 4.

Table 3 : Example of Survey Data

Server	%utilization	Time	Server	%utilization	Time	Server	%utilization	Time
005v	0	0	006v	0	0	007v	1	0
005v	0	30	006v	0	30	007v	28	30
005v	0	60	006v	0	60	007v	26	60
005v	0	90	006v	0	90	007v	24	90
005v	1	120	006v	0	120	007v	2	120

Experimental Equipment Setup

A Dell PowerEdge R720 with eight 10,000 RPM, 900 GB SAS harddrives, twenty-two 1600MHz 16GB DIMMs, and two 2.70GHz Xeon E5-2697 CPUs is used as the host system. Each Xeon CPU provides the host 12 cores. After Hyper-threading, the host operating system is presented 48 logical processors. There is a L1 cache of 1.5MB, a L2 cache of 6MB, and a L3 cache of 60MB. Harddrives 2 – 6 are combined into one 3353GB logical drive with Windows 2012 soft RAID-5. Harddrive 1 contains data unrelated to the project. Harddrive 7 is used to store installation files. Harddrive 8 is the system drive of the host operating system. The host system also has a 3000GB Fusion-io drive2 installed and recognized by the host operating system as disk 0, it is used as part of a tiered storage pool to overcome disk IO limitations found during early testing.

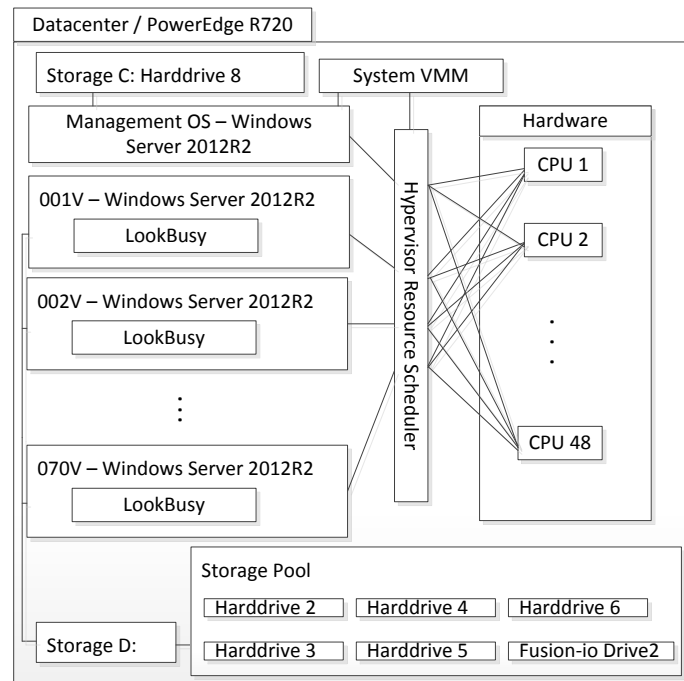


Figure 5. Experimental Equipment Setup and Configuration

Software Configuration

The software configuration, and key aspects of its interaction with hardware, is depicted in figure 5. Windows Server 2012R2 is used as the host operating system. The Hyper-V hypervisor is enabled allowing virtualization of additional guest operating systems (OS) and applications. The RAID-5 partition is labeled “D.” One virtual switch named “NIC0 Bridged” is created and associated with all guest OS. The host operating system is able to use this virtual switch to communicate with guest OS.

The guest operating systems are Windows Server 2012R2. One virtual machine was created with 8GB of RAM, 2 virtual CPU, and a virtual 60GB harddrive on the D drive. After installation of Windows Server 2012R2, Cygwin, Lookbusy, and `cpu-load-generator.py` are loaded and a scheduled task is created to start the simulation. The template virtual machine is shutdown and cloned to simulate an Air Force Data Center.

Simulation Generation

To create the data center workload trace twenty-seven samples, one per half hour over a fourteen hour period, were taken from 70 systems in the Air Force Data Center. These were then enumerated into trace files for use by `cpu-load-generator.py`. The simulation was configured to change state every 9 seconds with sampling every 3 seconds to satisfy Shannon's Theorem. Three simulation sets were created:

- Replay of survey data
- Random sampling of survey data set per application
- Random sampling of survey data set per unit time

The first simulation is intended to show validity of the simulation in a consolidated virtual environment and is expected to closely match the survey data which was taken from a distributed physical environment. The second simulation is intended to simulate the data center with an assumption that load between applications is not dependant on time. The third simulation is intended to simulation the data center with an assumption that load between applications is dependent on time. A python script was developed for the purpose of generating the second and third simulation sets and is included in Appendix A.

Workload Generation

The `cpu-load-generator.py` script was developed by Dr. Beloglazov as an open source tool to generate CPU load according to a configuration profile or workload trace. It uses Devin Carraway's open source tool Lookbusy to make an arbitrary number of CPUs arbitrarily busy. While Dr. Beloglazov used a web service to assign and trigger load profiles, in this simulation task scheduler is used with load profiles assigned by powershell script.

Each clone is configured with a CPU load profile based on measurements taken by the 38ES survey team. This allows the virtual environment to either replay real activity seen in a physical Air Force Data Center or run simulation scenarios described in the previous section.

Data Collection

The Windows Performance Monitoring tool, Perfmon, was used to collect data. Perfmon allows for the recording of hundreds of different counters. In the simulation phase, this study used several counters including [32]:

Table 4 : Windows Performance Monitoring Metrics

Metric	Description	Example
<Hyper-V Hypervisor Virtual Processor\CPU Wait Time Per Dispatch>	The average time (in nanoseconds) spent waiting for a virtual processor to be dispatched onto a logical processor	12699.25
< Hyper-V Hypervisor Virtual Processor(_Total)\% Total Run Time >	Shows the time the cpu is not idle across the Hyper-V environment	5.243332
<System\Processor Queue Length>	Shows the number of threads waiting to be serviced	0
< Hyper-V Hypervisor Virtual Processor(_Total)\% Hypervisor Run Time>	Slice of the % Total Run Time used by the Virtual Machine Manager	0.052604
< Hyper-V Hypervisor Virtual Processor(_Total)\% Guest Run Time>	Slice of the % Total Run Time used by guest virtual machines	5.190729
<System\File Write Operations/sec>	Shows the combined rate, in incidents per second, of file system write requests to all devices on the computer	61.32717
<System\File Read Operations/sec>	Shows the combined rate, in incidents per second, of file system read requests to all devices on the computer	60.66057
<System\File Control Operations/sec>	Shows the combined rate, in incidents per second, of file system operations that were neither read nor write operations.	271.6394

During data collection in the production environment, a PowerShell script was used to sample the Perfmon value for <System\% Processor Time> [33].

Analysis Methodology

There are five sections of data to be analyzed. Raw survey data, cumulative survey data, cumulative replay simulation data, cumulative application-based simulation data, and cumulative time-based simulation data. The raw survey data consists of CPU utilization measurements taken by the 38 ES survey team on a per application server basis. Cumulative survey data consists of CPU utilization measurements summed across all 70 application servers in the data center for each sample in time. The sum of all samples at $t=0$ is the cumulative CPU utilization at $t=0$, the sum of all samples at $t=30$ is the cumulative CPU utilization at $t=30$, and so on. All three Cumulative simulation data sets consist of total CPU utilization measurements from the hypervisor supporting the simulation. The cumulative simulation data sets offer a view into resource utilization in a fully virtual environment.

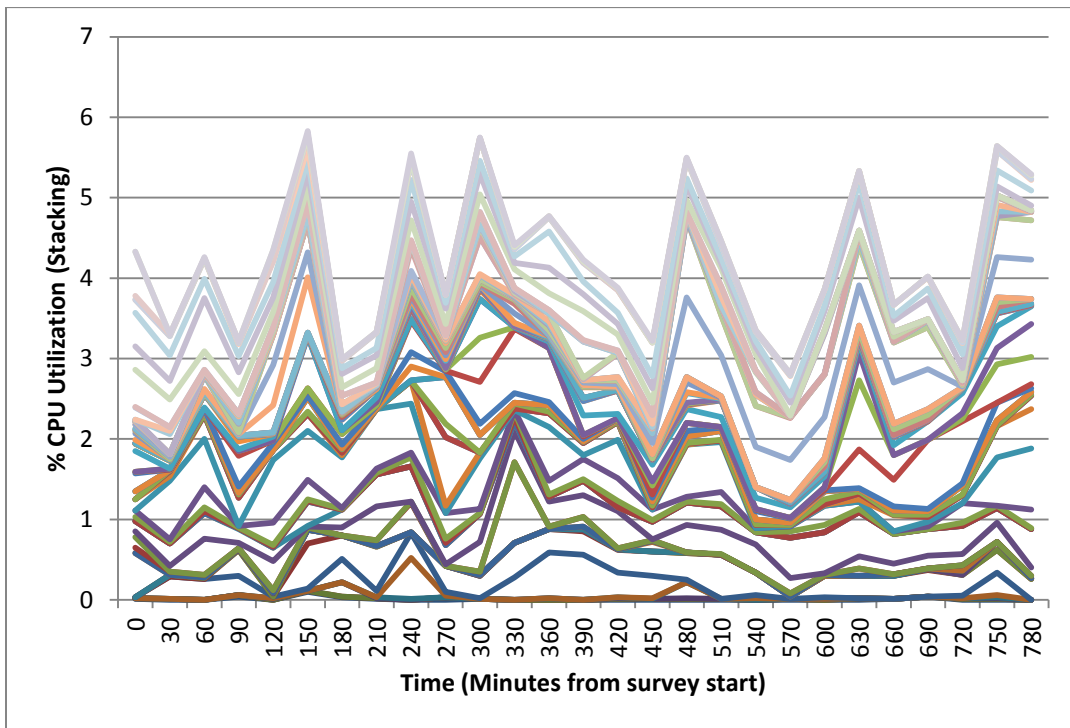


Figure 6. Cumulative CPU Utilization of Survey data, Stacked Line Plot

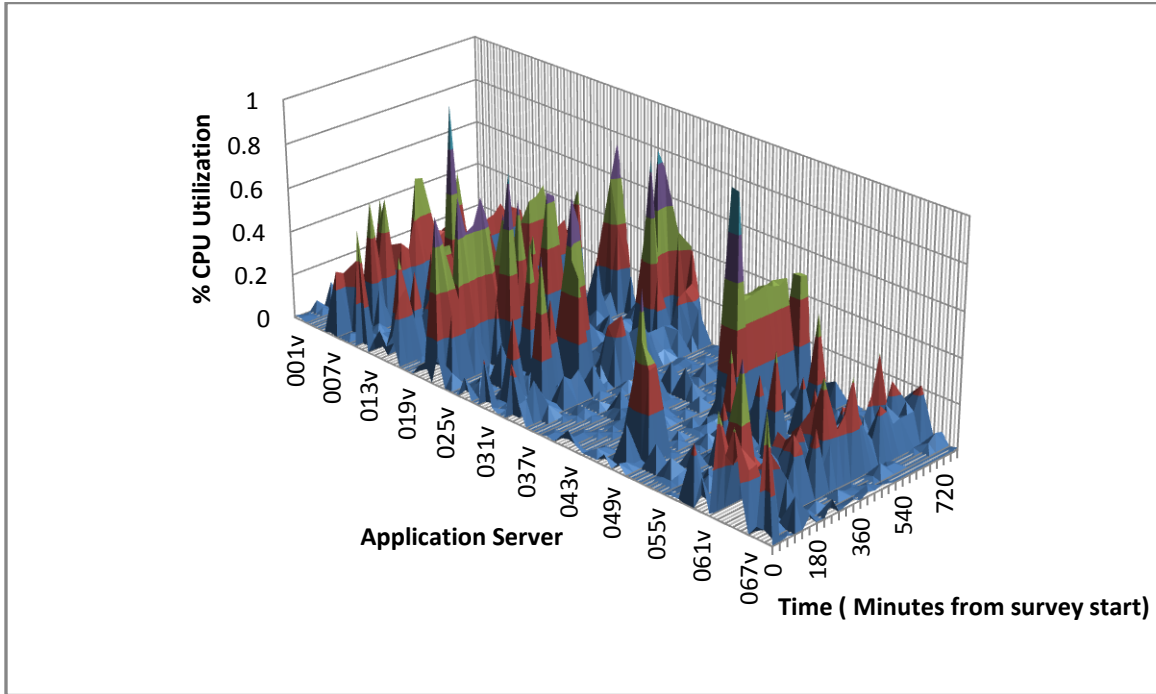


Figure 7. Surface Plot of Survey Data

The analysis methodology is based on chapter 2 findings for Erlang's formulae and more generally for statistical analysis from the Engineering Statistics Handbook. For each data set, descriptive statistical values for minimum, maximum, mean and standard deviation are calculated. A histogram is plotted then compared by correlation with Erlang's formulae then with the Erlang, Gamma and Gaussian-Normal distributions. As noted above, the Erlang distribution will be calculated by rounding the α parameter to the nearest integer.

IV. Analysis and Results

Chapter Overview

In this part the results obtained by calculation from measurements obtained during survey, as well as during simulation and compare with Erlang, Gamma, and Gaussian-Normal distributions are presented.

Descriptive Statistical Analysis

Appendix B includes an anonymized version of Windows Performance Monitor <System\% Processor Time> data collected during the survey of an Air Force Data Center. Server names were replaced with numbers from 001v to 070v.

Since the Performance Monitor results were collected into a csv format, Excel was used to calculate descriptive statistics that summarize the raw survey data. Table 5 compares these statistics. All values, except for sample count, are expressed in terms of physical CPU cores.

A median value of zero for Raw Survey Data indicates that at least 50% of samples reported no server activity, emphasizing possible efficiencies to be found in virtualization and consolidation by showing that over 50% of the time data center assets are simply waiting for work.

Table 5 : Comparison of Descriptive Statistics for Each Data Set

Survey Data		Cumulative Survey Data		Cumulative Replay Simulation Data	
Minimum	0	Minimum	2.81	Minimum	2.59
Maximum	1	Maximum	5.83	Maximum	14.1
Mean	0.0629	Mean	4.24	Mean	4.60
Median	0	Median	4.23	Median	4.63
Samples	1838	Samples	27	Samples	2850
Standard Deviation	0.136	Standard Deviation	0.937	Standard Deviation	0.814
		Cumulative App-based Simulation Data		Cumulative Time-based Simulation Data	
		Minimum	2.16	Minimum	2.19
		Maximum	9.3	Maximum	8.4
		Mean	4.59	Mean	4.56
		Median	4.55	Median	4.52
		Samples	5401	Samples	5401
		Standard Deviation	0.651	Standard Deviation	0.810

For most cumulative data sets, the minimum, mean, and standard deviation of CPU utilization are similar. The cumulative app-based simulation data set shows a smaller standard deviation when compared with the other simulation scenarios and results in a larger α value and smaller β value per definitions for equations 6 and 7 as well as slightly lower predictions for hardware requirements.

Analysis of Fit of Erlang's Formulae

The second part of analysis uses equations 8 and 9 to attempt to size a data center. The descriptive parameters of mean CPU utilization, A , is used together with various numbers of CPU cores available for traffic, N , then compared with the inverse cumulative distribution of the observed datasets.

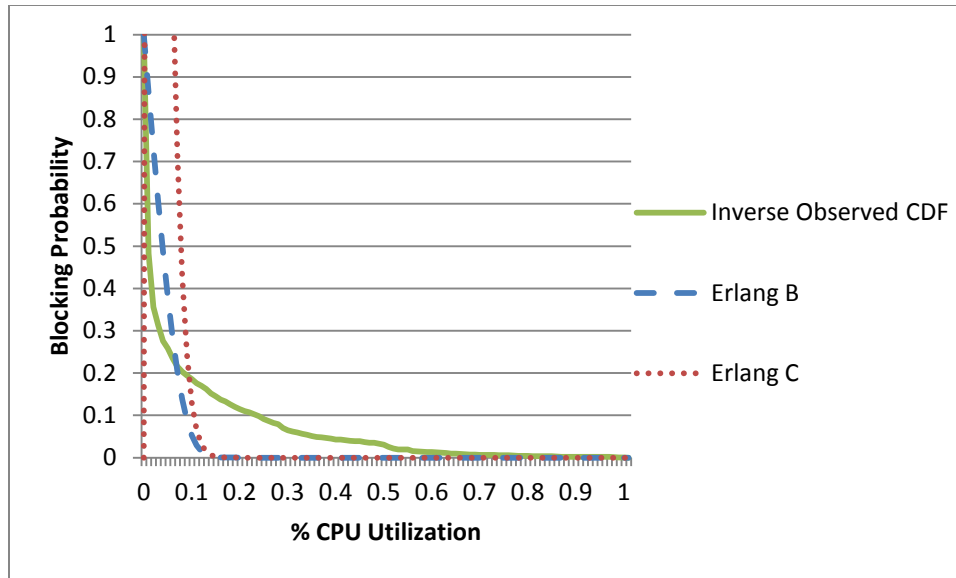


Figure 8. Comparison of Erlang B and C with Survey Data

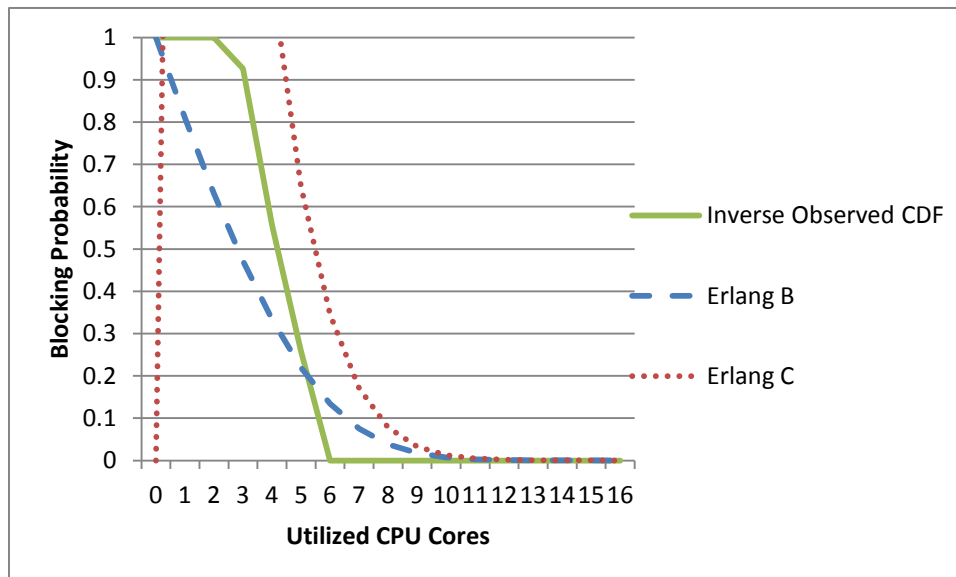


Figure 9. Comparison of Erlang B and C with Cumulative Survey Data

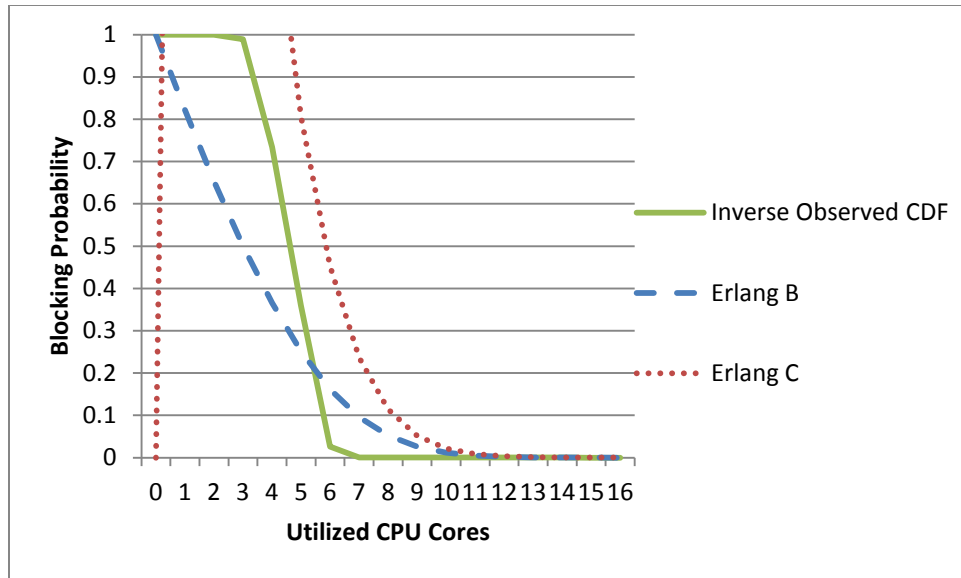


Figure 10. Comparison of Erlang B and C with Cumulative Replay Simulation Data

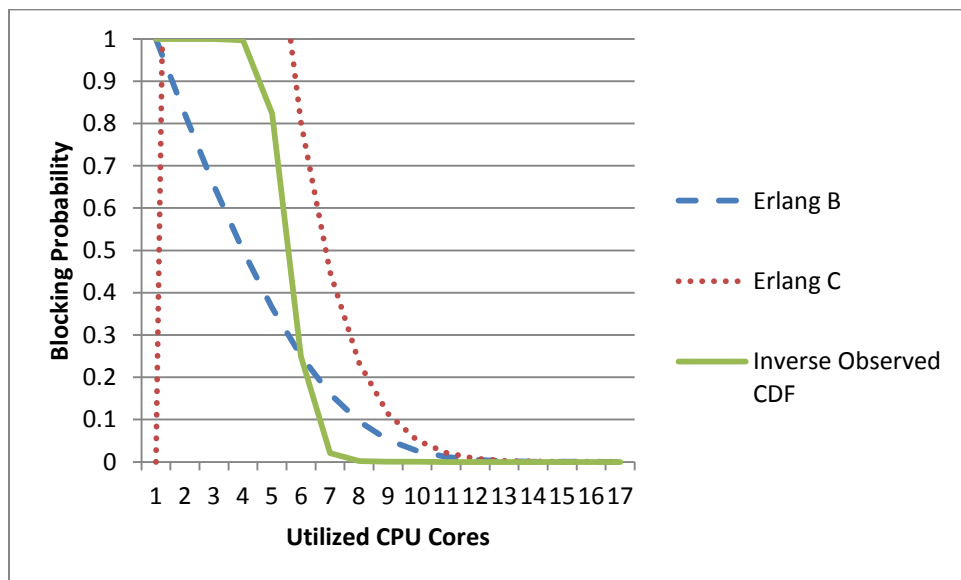


Figure 11. Comparison of Erlang B and C with Cumulative App-based Simulation Data

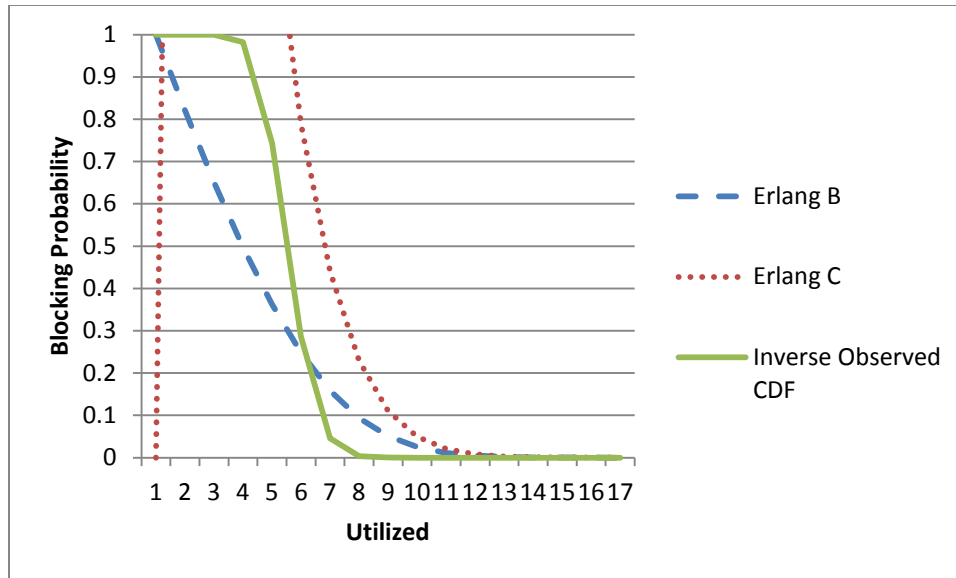


Figure 12. Comparison of Erlang B and C with Cumulative Time-based Simulation Data

The Erlang B and Erlang C formulae do not appear to be a good fit in figures 8 - 12. Calculation of correlation coefficients in table 6 shows some degree of correlation.

Table 6 : Comparison of Erlang Formulae Correlation Coefficients for Each Data Set

	Erlang B	Erlang C
Cumulative Survey Data	0.950820839	0.937472778
Cumulative Replay Simulation Data	0.941291397	0.921250068
Cumulative App-based Simulation Data	0.931956494	0.911316961
Cumulative Time-based Simulation Data	0.941643605	0.922631406
Raw Survey Data	0.877987087	0.791652648

Other inferential statistical methods discussed in Chapters 2 and 3 are next pursued.

Inferential Statistical Analysis

The third part of analysis uses descriptive parameters calculated in the previous section as inputs to known statistical distributions and will use correlation coefficients to find best fitting distributions. Beginning with the raw survey data, visualized in Figure 13, it is shown that the Gamma distribution is a very close match to the observed data. It is also apparent that the Erlang distribution is not a good fit here. This is caused by the distribution shape parameter for the Erlang distribution, α , which in this case was less than 0.5 to begin with, being rounded to the nearest positive integer of 1. As per equations 6 and 7, the distribution shape is a product of μ^2 / σ^2 , or A^2 / σ^2 when translated by the modified parameters table, table 2.

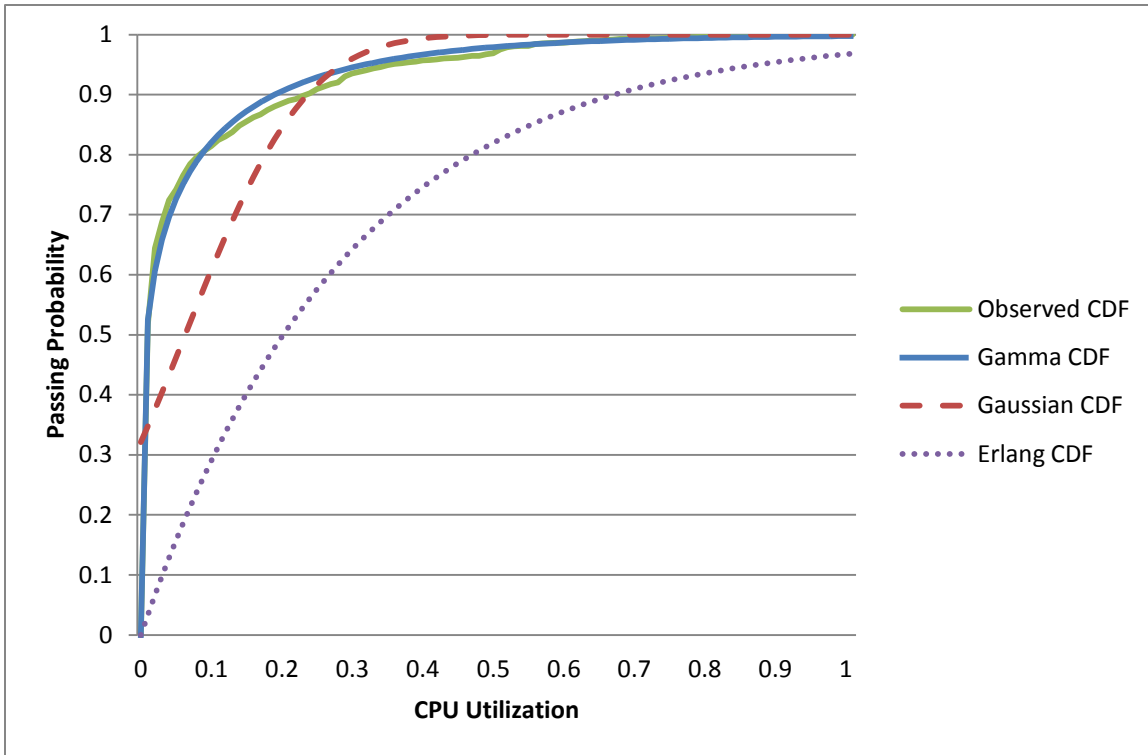


Figure 13. Raw Survey Data – Comparison of Observed, Gamma ($\alpha = 0.215$, $\beta = 0.292$), Gaussian-Normal ($\mu = 0.063$, $\sigma = 0.136$) and Erlang ($\alpha = 1$, $\beta = 0.292$) Distributions

The Erlang, Gamma, and Gaussian-Normal distributions are compared with the observed replay simulation data in Figures 14, 15, and 16. The same distributions are compared with the application based simulation data in Figures 17, 18, 19 and again with the time based simulation data in Figures 20, 21, and 22. Each comparison was split out into its own figure to improve readability. Each of the three distributions match so closely, however, it is still difficult to differentiate between the two curves.

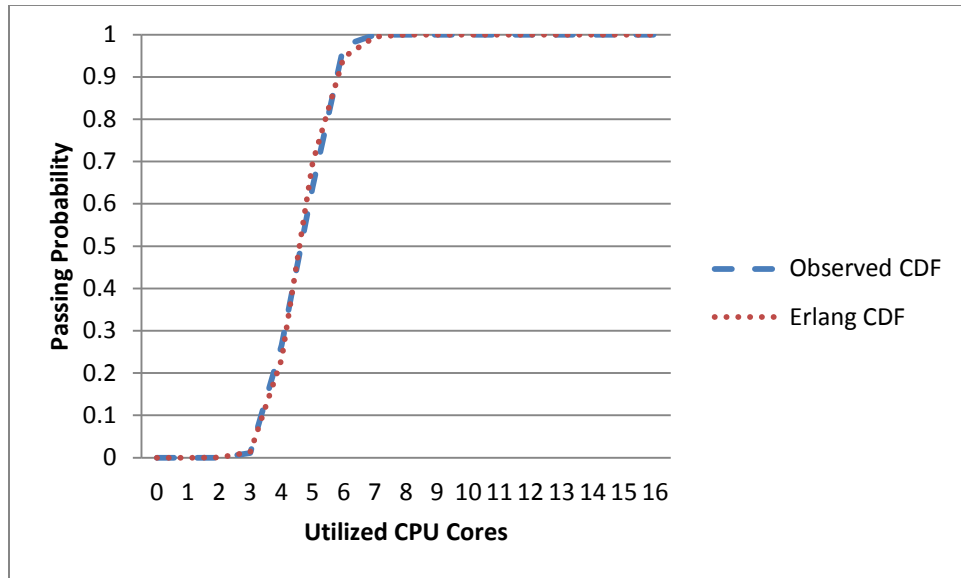


Figure 14. Cumulative Replay Simulation Data – Observed CDF vs Erlang Distribution CDF ($\alpha = 32, \beta = 0.14419$)

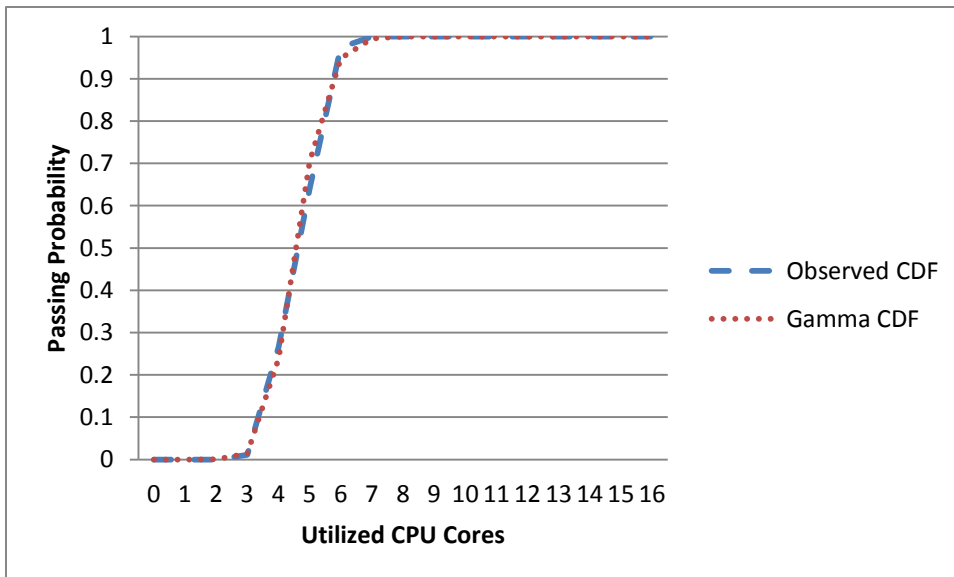


Figure 15. Cumulative Replay Simulation Data – Observed CDF vs Gamma Distribution CDF ($\alpha = 31.901, \beta = 0.14419$)

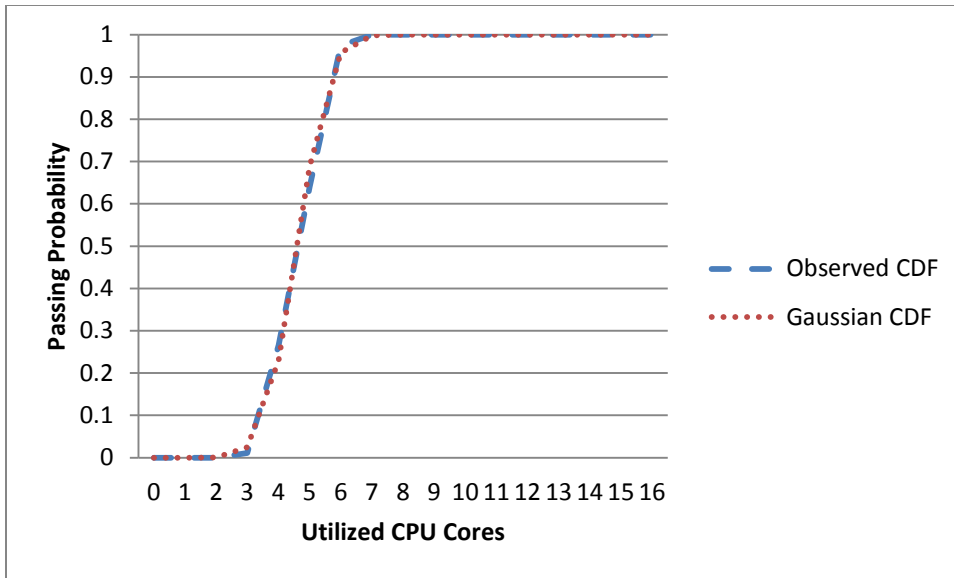


Figure 16. Cumulative Replay Simulation Data – Observed CDF vs Gaussian-Normal Distribution CDF ($\mu = 4.5999$, $\sigma = 0.81441$)

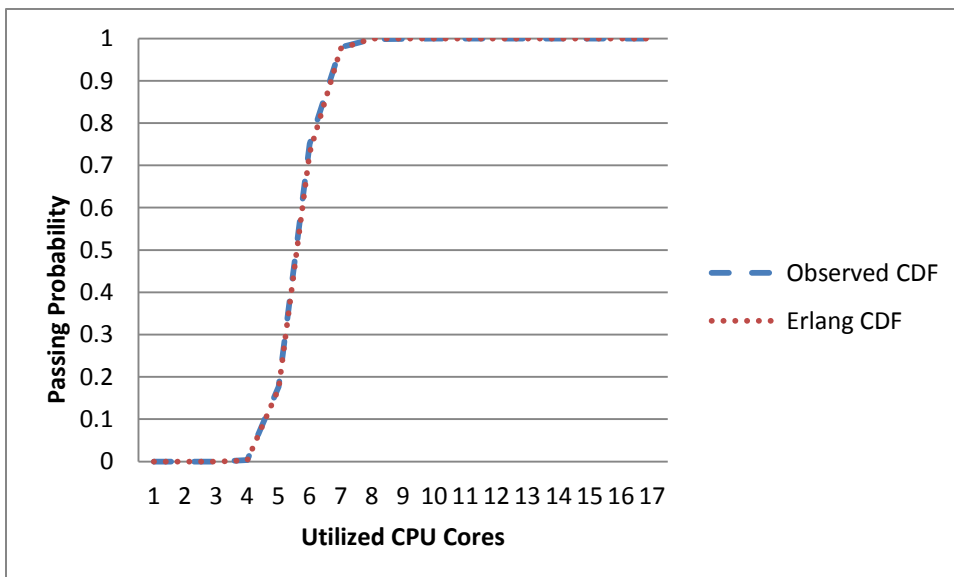


Figure 17. Cumulative App-based Simulation Data - Observed CDF vs Erlang Distribution CDF ($\alpha = 50$, $\beta = 0.092395$)

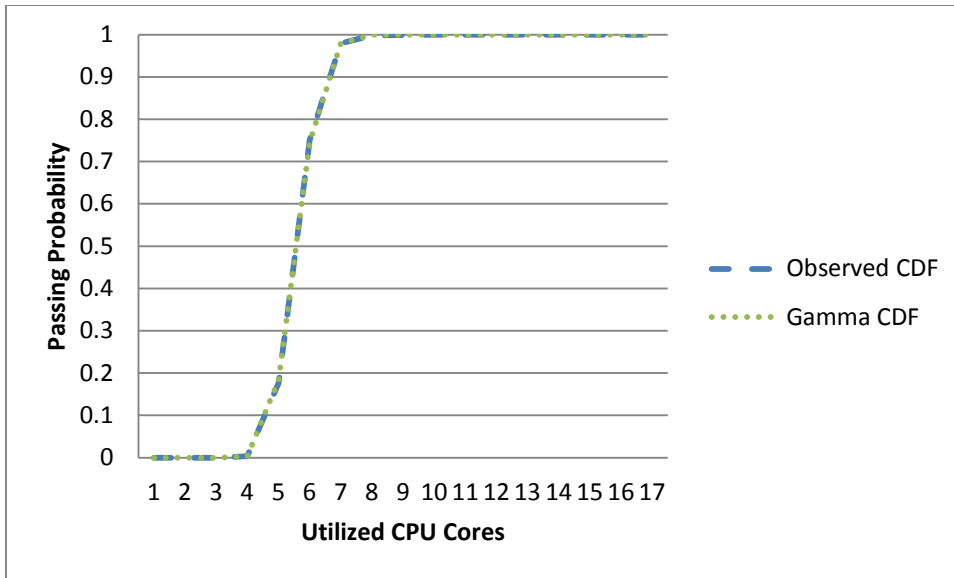


Figure 18. Cumulative App-based Simulation Data – Observed CDF vs Gamma Distribution CDF ($\alpha = 49.664$, $\beta = 0.092395$)

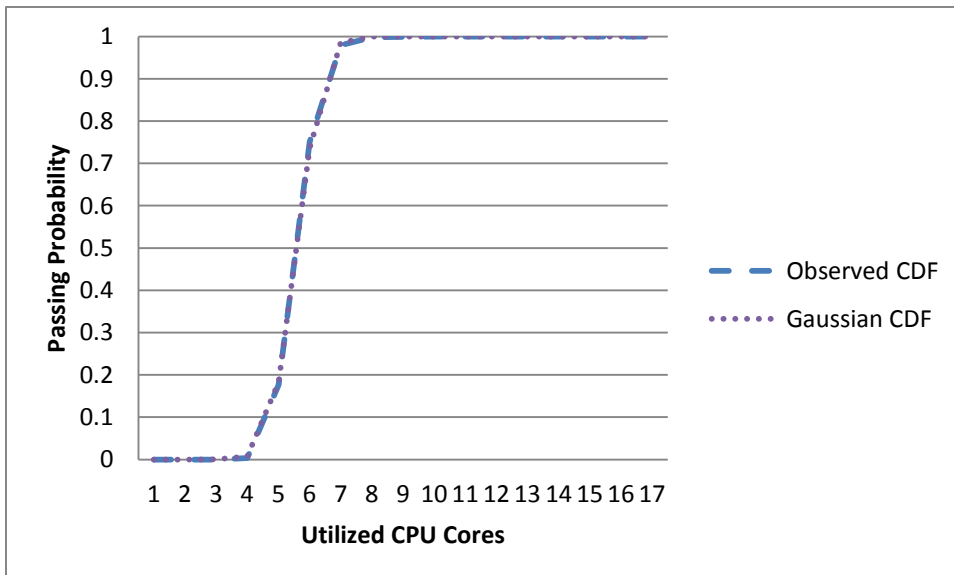


Figure 19. Cumulative App-based Simulation Data – Observed CDF vs Gaussian-Normal Distribution CDF ($\mu = 4.5888$, $\sigma = 0.65114$)

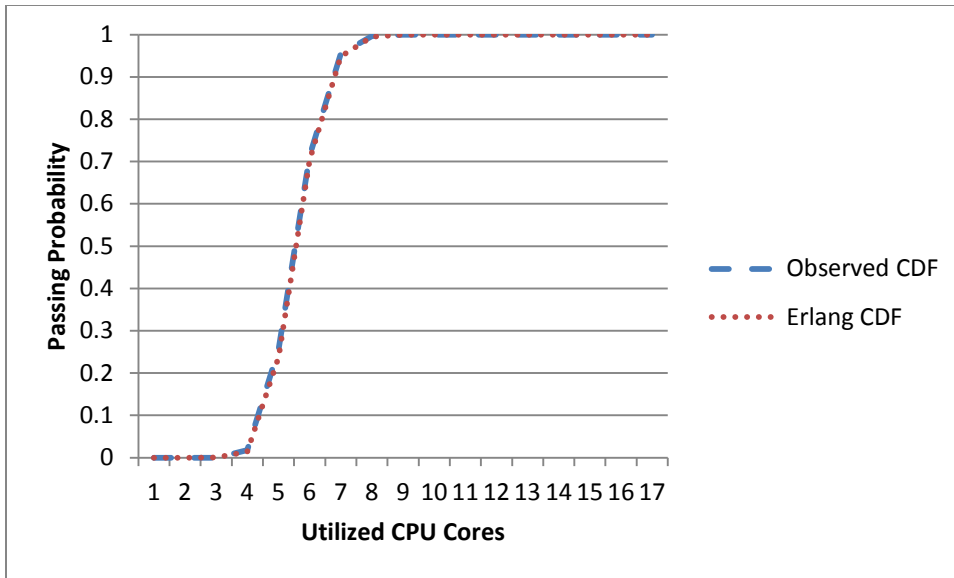


Figure 20. Cumulative Time-based Simulation Data - Observed CDF vs Erlang Distribution CDF ($\alpha = 32$, $\beta = 0.14377$)

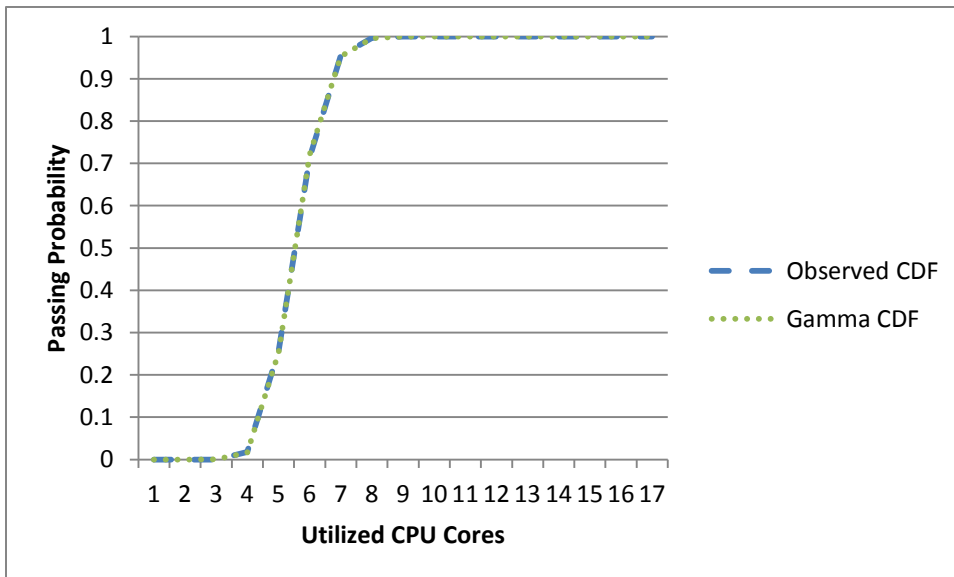


Figure 21. Cumulative Time-based Simulation Data – Observed CDF vs Gamma Distribution CDF ($\alpha = 31.727$, $\beta = 0.14377$)

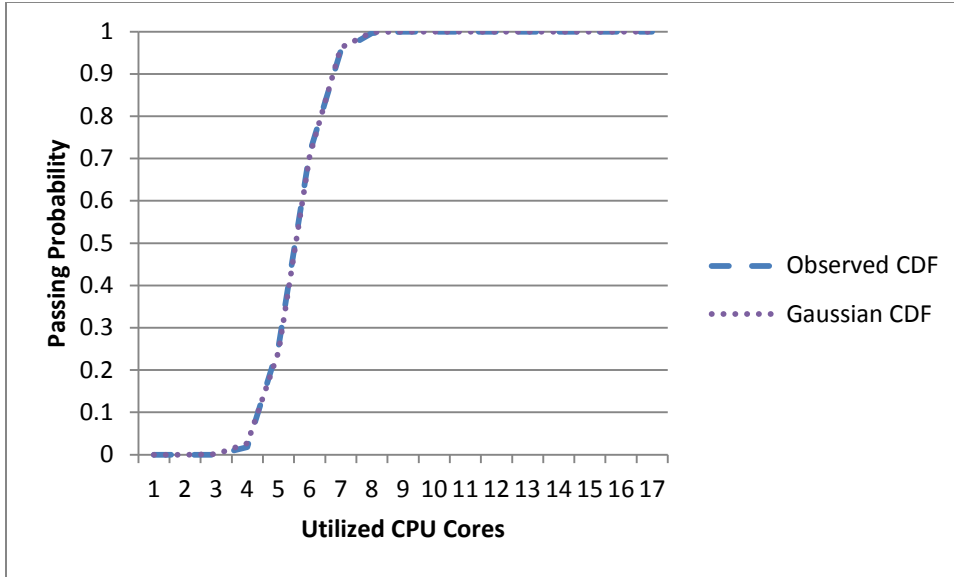


Figure 22. Cumulative Time-based Simulation Data – Observed CDF vs Gaussian-Normal Distribution CDF ($\mu = 4.5229$, $\sigma = 0.80984$)

In order to overcome the limitations of the graphs, correlation coefficients are shown in table 7. It is shown that for cumulative data sets, all three distributions are good fits and that the Gaussian-Normal distribution provides the best fit. For the raw survey data it is shown that the Gamma distribution provides the best fit.

Table 7 : Comparison of Distribution Correlation Coefficients for Each Data Set

	Erlang CDF	Gamma CDF	Gaussian CDF
Cumulative Survey Data	0.998495255	0.999039326	0.998980715
Cumulative Replay Simulation Data	0.999155381	0.999106357	0.999349484
Cumulative App-based Simulation Data	0.999935781	0.999986389	0.999953034
Cumulative Time-based Simulation Data	0.999936780	0.999991168	0.999937383
Raw Survey Data	0.8272*	0.99664592	0.862088045

* Could not be calculated because α was too small after rounding

In trying to understand these results, it is important to recall the Central Limit Theorem. While individual application workloads do not appear to be best fit by a Gaussian-Normal distribution, the hypervisor is essentially performing convolution of the various distributions representing each individual application in the data center. As such, for a sufficiently large number of applications virtualized in a data center, the distribution will tend towards Gaussian-normal.

Contrasting with Sixty Percent Rule

The Sixty Percent Rule discussed in Chapter 1, and used by the 38th CEIG team during early planning efforts, multiplies mean utilization measured during the survey (4.24) by 1.6 then rounds up to the nearest integer. Table 8 compares.

Table 8 : Comparison of Estimated CPU Requirements

	CPU Cores Required (5 9s)	CPU Cores Required (3 9s)
Cumulative Survey Data - Gaussian	9	8
Cumulative Replay Simulation Data - Gaussian	9	8
Cumulative App-based Simulation Data - Gaussian	8	7
Cumulative Time-based Simulation Data - Gaussian	9	8
Cumulative Survey Data - Gamma	10	8
Cumulative Replay Simulation Data - Gamma	9	8
Cumulative App-based Simulation Data - Gamma	8	7
Cumulative Time-based Simulation Data - Gamma	9	8
Cumulative Survey Data - Erlang	10	8
Cumulative Replay Simulation Data - Erlang	9	8
Cumulative App-based Simulation Data - Erlang	8	7
Cumulative Time-based Simulation Data - Erlang	9	8

Cumulative Survey Data - Erlang B	14	13
Cumulative Replay Simulation Data - Erlang B	15	13
Cumulative App-based Simulation Data - Erlang B	15	13
Cumulative Time-based Simulation Data - Erlang B	15	13
Cumulative Survey Data - Erlang C	15	13
Cumulative Replay Simulation Data - Erlang C	15	14
Cumulative App-based Simulation Data - Erlang C	15	14
Cumulative Time-based Simulation Data - Erlang C	15	13
Sixty Percent Rule	7	7

Evidently, the Sixty Percent Rule matches up with Gaussian, Erlang and Gamma distribution predictions for a data center with 3 nines reliability under the Application based simulation scenario. Under all other scenarios, including calculations based off of the survey data itself, the Sixty Percent Rule under estimates the hardware requirement.

Investigative Questions Answered

1. What are the prevalent metrics for computer processing emphasized by current practice, or found in the academic body of knowledge?

In research, the majority of the academic body of knowledge centers around optimization of data center (electrical) power, (network) ping, and (cooling) pipes. It has perhaps been the prevalence of Moore's Law, popularly thought of as processor power doubling every 18 months, that has left the topic of estimating processing requirements in neglect.

2. How well does an Erlang distribution approximate data center CPU load?

A quirk of the Erlang distribution is a parameter of the distribution must be a positive integer. During the analysis of the collected data, the Gamma

distribution's CDF (which is the same as the Erlang distribution sans the integer requirement) was used and found to strongly correlate to both the simulation and survey datasets. For the simulation datasets, with over 2000 samples, a normal distribution was found to high slightly higher correlation coefficient than a gamma distribution, 0.9993 compared to 0.9991. For the survey data, with only 27 samples, the reverse was true, gamma distribution CDF correlation coefficient 0.9990 compared to normal distribution CDF of 0.9989. This is not a significant difference in correlation. In cases where there are fewer virtual servers in the environment it should be expected for the gamma distribution to be more reliable whereas in environments with many virtual servers, such as the 70 found in the 38th ES survey and simulated as part of this thesis, the Gaussian-Normal distribution has been shown to be reliable as well.

3. How should processing in data centers or IaaS projects be sized?

Since the Erlang/Gamma distribution was shown to be a good fit for the observed data, IaaS and data center projects may use Erlang's distribution, Gamma distribution, or Gaussian-Normal distribution to help size necessary processing capacity. In situations where a small number of servers are being virtualized, the Gamma distribution was found to be the most accurate. Where a large number of servers are being virtualized, the Gaussian-Normal distribution should be used to minimize waste capacity.

V. Conclusions and Recommendations

Chapter Overview

In this chapter, conclusions and recommendations for action and future research are presented.

Conclusions of Research

By analogy, Erlang's formulae for the probability of blocking and queuing were expected to be applicable to cumulative CPU utilization in a data center. One assumption of the Erlang formulae is that the traffic essentially follows an exponential distribution. While this was found to be true for individual applications, it was not so once the hypervisor convoluted dozens of virtual applications against limited physical resources. The research shows the distribution of cumulative CPU utilization across a large number of applications (70 application servers in the survey and simulation) can be described by the Erlang/Gamma distribution and Normal distribution. While it appears that Erlang's formulae, with minor modification discussed in chapter 3, can be used for CPU loads, a normal distribution is more accurate.

This is significant to Air Force Data Center Consolidation efforts because it allows planners to estimate how much consolidation can take place using existing resources and what new resources will be required to reach the end state. Without a method for parametric estimation of load in Air Force datacenters, planners are forced to make wild guesses at the requirement. This leads to either over purchasing hardware to avoid the risk of not having enough, which wastes money, or under purchase hardware for lack of justification, which reduces reliability and increases latency of Air Force

Enterprise applications running in the datacenter like Active Directory Services and Microsoft Exchange.

Recommendations for Action

Statistical analysis, taking advantage of either Gamma or Gaussian-Normal distribution, should be used to test if processing capacity is a likely cause of delay when sizing and troubleshooting virtual environments. As a practical example, if an availability of 5 nines is required for a base level data center then mean cumulative CPU utilization plus 5 standard deviations calculates the processing requirement before any additional redundancy requirements are introduced.

Recommendations for Future Research

Future research should include analysis of changes to cumulative CPU utilization induced by hypervisor co-scheduling processes and methods for predicting mean CPU utilization in virtual environments based on measurements of the same application on a physical host. Future research might also include investigation of the use of Markov chains as statistical models to better predict CPU utilization.

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Appendix A: Testbed Setup and Configuration

Cygwin was installed to allow for the use of the open source load generator LookBusy. A python script originally written by Anton Beloglazov was used to control the LookBusy load generator. Cygwin needed the Archive, Python, WEB->wget, DEVEL->gcc, and DEVEL->make packages included for successful installation and operation.

Survey Dataset

This file is used as an input to the simulation-generator.py script



LB Utilization.csv

Simulation-generator.py

```
# Copyright 2015 Derek Molle
# Usage of the works is permitted provided that this instrument is
# retained with the works, so that any entity that uses the works is
# notified of this instrument. Disclaimer: The works are without
# warranty.
# This script uses LB Utilization.csv to generate two folders of
# simulation files for use by cpu-load-generator.py: asim where a
# simulation is generated using application behavior as basis. tsim
# where a simulation is generated using data center behavior at each
# moment in time as a basis
import csv
import random
# number of simulations to generate for both application and time
# methods
numsimulations = 100
with open('LB Utilization.csv', 'rb') as surveydatafile:
    csvdata = csv.DictReader(surveydatafile)
    data = {x.strip():[y] for x,y in csvdata.next().items()}

    for rows in csvdata:
        for x,y in rows.items():
            data[x.strip()].append(y)
print len(data['Time'])
timedistributions = {x.strip():[] for x in set(data['Time'])}
appdistributions = {x.strip():[] for x in set(data['App'])}
for t, u, a in zip(data['Time'],data['Utilization'],data['App']):
    timedistributions[t.strip()].append(u)
    appdistributions[a.strip()].append(u)

LBAppfiles = {x.strip():[] for x in set(data['App'])}
```

```

LBTimefiles = {x.strip():[] for x in set(data['App'])}

for x in LBAppfiles:
    LBAppfiles[x] = [random.choice(appdistributions[x]) for _
in xrange(numsimulations*27)]

    for _ in xrange(numsimulations):
        for t in set(data['Time']):
            for x in LBTimefiles:

LBTimefiles[x].append(random.choice(timedistributions[t]))
path = "asim\\"
for x in LBAppfiles:
    file=open(path+x+".txt",'w')
    for y in LBAppfiles[x]:
        file.write("%s\n" % y)
path = "tsim\\"
for x in LBTimefiles:
    file=open(path+x+".txt",'w')
    for y in LBTimefiles[x]:
        file.write("%s\n" % y)

```

cpu-load-generator.py

```

# Copyright 2012 Anton Beloglazov
#
# Licensed under the Apache License, Version 2.0 (the "License");
# you may not use this file except in compliance with the License.
# You may obtain a copy of the License at
#
#     http://www.apache.org/licenses/LICENSE-2.0
#
# Unless required by applicable law or agreed to in writing, software
# distributed under the License is distributed on an "AS IS" BASIS,
# WITHOUT WARRANTIES OR CONDITIONS OF ANY KIND, either express or
# implied.
# See the License for the specific language governing permissions and
# limitations under the License.

""" A tool for generating a set of subsequent CPU utilization levels.
"""

from optparse import OptionParser, Option, IndentedHelpFormatter
import os
import subprocess
import time

def process(interval, utilization_list, ncpus):
    ncpus_str = str(ncpus)
    for utilization in utilization_list:
        utilization_str = str(utilization)
        print "\nSwitching to " + utilization_str + "%"
        p = subprocess.Popen(['lookbusy',
                               '--ncpus', ncpus_str,

```



```

        '--cpu-util', utilization_str])
    time.sleep(interval)
    p.terminate()

class PosOptionParser(OptionParser):

    def format_help(self, formatter=None):
        class Positional(object):
            def __init__(self, args):
                self.option_groups = []
                self.option_list = args

        positional = Positional(self.positional)
        formatter = IndentedHelpFormatter()
        formatter.store_option_strings(positional)
        output = ['\n', formatter.format_heading('Positional
Arguments')]
        formatter.indent()
        pos_help = [formatter.format_option(opt) for opt in
self.positional]
        pos_help = [line.replace('--', '') for line in pos_help]
        output += pos_help
        return OptionParser.format_help(self, formatter) +
''.join(output)

    def add_positional_argument(self, option):
        try:
            args = self.positional
        except AttributeError:
            args = []
        args.append(option)
        self.positional = args

    def set_out(self, out):
        self.out = out

def main():
    parser = PosOptionParser(
        usage='Usage: python %prog [options] INTERVAL SOURCE',
        description='Generates a set of subsequent ' +
            'CPU utilization levels read from a file. ' +
            ', ' +
            'Copyright (C) 2012 Anton Beloglazov. ' +
            'Released under Apache 2.0 license.')
    parser.add_positional_argument(
        Option('--INTERVAL', action='store_true',
            help='interval between subsequent CPU ' +
            'utilization levels in seconds'))
    parser.add_positional_argument(
        Option('--SOURCE', action='store_true',
            help='source file containing a new line ' +
            'separated list of CPU utilization levels ' +
            'specified as numbers in the [0, 100] range'))

```

```

    parser.add_option('-n', '--ncpus', type='int', dest='ncpus',
default=1,
                        help='number of CPU cores to utilize [default:
1]')

(options, args) = parser.parse_args()

if len(args) != 2:
    parser.error('incorrect number of arguments')

try:
    interval = int(args[0])
except ValueError:
    parser.error('interval must be an integer >= 0')
if interval <= 0:
    parser.error('interval must be an integer >= 0')

filename = args[1]
if not os.access(filename, os.R_OK):
    parser.error('cannot read file: ' + filename)

utilization = []
for line in open(filename):
    if line.strip():
        try:
            n = float(line)
            if n < 0 or n > 100:
                raise ValueError
            utilization.append(int(n))
        except ValueError:
            parser.error('the source file must only ' +
                        'contain new line separated ' +
                        'numbers in the [0, 100] range')

if interval <= 0:
    parser.error('interval must be an integer >= 0')

process(interval, utilization, options.ncpus)

if __name__ == '__main__':
    main()

```

lb.c - Lookbusy



LB.c.docx

Appendix B: Survey Information

Filename	%util	Time	Filename	%util	Time	Filename	%util	Time	Filename	%util	Time
001v	1	0	002v	1	0	003v	0	0	004v	0	0
001v	0	30	002v	1	30	003v	0	30	004v	0	30
001v	0	60	002v	0	60	003v	0	60	004v	0	60
001v	4	90	002v	2	90	003v	0	90	004v	0	90
001v	0	120	002v	0	120	003v	0	120	004v	1	120
001v	10	150	002v	1	150	003v	0	150	004v	0	150
001v	3	180	002v	1	180	003v	0	180	004v	18	180
001v	1	210	002v	1	210	003v	0	210	004v	0	210
001v	0	240	002v	0	240	003v	0	240	004v	0	240
001v	0	270	002v	3	270	003v	0	270	004v	0	270
001v	1	300	002v	0	300	003v	0	300	004v	0	300
001v	0	330	002v	0	330	003v	0	330	004v	0	330
001v	0	360	002v	0	360	003v	0	360	004v	2	360
001v	0	390	002v	0	390	003v	0	390	004v	0	390
001v	0	420	002v	1	420	003v	0	420	004v	1	420
001v	0	450	002v	1	450	003v	0	450	004v	0	450
001v	0	480	002v	1	480	003v	0	480	004v	1	480
001v	0	510	002v	1	510	003v	0	510	004v	0	510
001v	0	540	002v	0	540	003v	0	540	004v	0	540
001v	0	570	002v	1	570	003v	0	570	004v	0	570
001v	0	600	002v	0	600	003v	0	600	004v	1	600
001v	0	630	002v	2	630	003v	0	630	004v	0	630
001v	1	660	002v	0	660	003v	0	660	004v	0	660
001v	4	690	002v	0	690	003v	0	690	004v	0	690
001v	0	720	002v	1	720	003v	0	720	004v	1	720
001v	0	750	002v	1	750	003v	0	750	004v	1	750
001v	0	780	002v	0	780	003v	0	780	004v	0	780
005v	0	0	002v	0	810	003v	0	810	004v	0	810
005v	0	30	006v	0	0	007v	1	0	008v	0	0
005v	0	60	006v	0	30	007v	28	30	008v	0	30
005v	0	90	006v	0	60	007v	26	60	008v	0	60
005v	1	120	006v	0	90	007v	24	90	008v	32	90
005v	0	150	006v	0	120	007v	2	120	008v	0	120
005v	0	180	006v	0	150	007v	3	150	008v	56	150
005v	1	210	006v	0	180	007v	29	180	008v	29	180
005v	1	240	006v	0	210	007v	8	210	008v	55	210
005v	0	270	006v	51	240	007v	31	240	008v	1	240

005v	0	300	006v	2	270	007v	5	270	008v	32	270
005v	0	330	006v	0	300	007v	1	300	008v	28	300
005v	0	360	006v	0	330	007v	28	330	008v	43	330
005v	0	390	006v	0	360	007v	57	360	008v	29	360
005v	1	420	006v	0	390	007v	56	390	008v	29	390
005v	0	450	006v	0	420	007v	31	420	008v	28	420
005v	20	480	006v	1	450	007v	28	450	008v	30	450
005v	0	510	006v	0	480	007v	3	480	008v	33	480
005v	0	540	006v	0	510	007v	0	510	008v	55	510
005v	0	570	006v	2	540	007v	4	540	008v	28	540
005v	0	600	006v	0	570	007v	0	570	008v	3	570
005v	0	630	006v	0	600	007v	2	600	008v	27	600
005v	0	660	006v	0	630	007v	0	630	008v	28	630
005v	0	690	006v	0	660	007v	0	660	008v	29	660
005v	0	720	006v	0	690	007v	0	690	008v	33	690
005v	1	750	006v	0	720	007v	3	720	008v	26	720
005v	0	780	006v	3	750	007v	28	750	008v	28	750
005v	1	810	006v	0	780	007v	0	780	008v	26	780
009v	0	0	006v	19	810	011v	0	0	008v	28	810
009v	2	30	010v	0	0	011v	0	30	012v	55	0
009v	1	60	010v	0	30	011v	0	60	012v	0	30
009v	0	90	010v	1	60	011v	1	90	012v	0	60
009v	0	120	010v	1	90	011v	1	120	012v	0	90
009v	17	150	010v	4	120	011v	0	150	012v	0	120
009v	0	180	010v	0	150	011v	0	180	012v	0	150
009v	0	210	010v	0	180	011v	0	210	012v	0	180
009v	0	240	010v	1	210	011v	0	240	012v	0	210
009v	0	270	010v	0	240	011v	0	270	012v	0	240
009v	0	300	010v	0	270	011v	1	300	012v	0	270
009v	0	330	010v	0	300	011v	0	330	012v	0	300
009v	0	360	010v	0	330	011v	0	360	012v	0	330
009v	2	390	010v	0	360	011v	1	390	012v	0	360
009v	1	420	010v	0	390	011v	0	420	012v	3	390
009v	0	450	010v	0	420	011v	0	450	012v	0	420
009v	0	480	010v	0	450	011v	0	480	012v	12	450
009v	0	510	010v	1	480	011v	0	510	012v	0	480
009v	0	540	010v	0	510	011v	0	540	012v	0	510
009v	0	570	010v	0	540	011v	0	570	012v	0	540
009v	0	600	010v	0	570	011v	0	600	012v	0	570
009v	0	630	010v	0	600	011v	0	630	012v	0	600
009v	0	660	010v	0	630	011v	0	660	012v	0	630

009v	1	690	010v	0	660	011v	1	690	012v	2	660
009v	0	720	010v	0	690	011v	5	720	012v	0	690
009v	0	750	010v	0	720	011v	0	750	012v	0	720
009v	0	780	010v	10	750	011v	0	780	012v	0	750
009v	0	810	010v	1	780	015v	13	0	012v	0	780
013v	0	0	014v	7	0	015v	0	30	016v	7	0
013v	0	30	014v	4	30	015v	0	60	016v	7	30
013v	0	60	014v	3	60	015v	0	90	016v	45	60
013v	0	90	014v	0	90	015v	0	120	016v	7	90
013v	0	120	014v	3	120	015v	0	150	016v	36	120
013v	0	150	014v	3	150	015v	0	180	016v	1	150
013v	0	180	014v	0	180	015v	0	210	016v	10	180
013v	0	210	014v	7	210	015v	1	240	016v	42	210
013v	0	240	014v	37	240	015v	0	270	016v	0	240
013v	0	270	014v	0	270	015v	0	300	016v	2	270
013v	0	300	014v	4	300	015v	0	330	016v	37	300
013v	0	330	014v	100	330	015v	0	360	016v	39	330
013v	0	360	014v	3	360	015v	0	390	016v	31	360
013v	0	390	014v	12	390	015v	0	420	016v	27	390
013v	0	420	014v	1	420	015v	0	450	016v	46	420
013v	1	450	014v	1	450	015v	0	480	016v	1	450
013v	0	480	014v	0	480	015v	1	510	016v	34	480
013v	0	510	014v	0	510	015v	0	540	016v	30	510
013v	0	540	014v	0	540	015v	0	570	016v	35	540
013v	0	570	014v	4	570	015v	0	600	016v	19	570
013v	1	600	014v	0	600	015v	0	630	016v	2	600
013v	0	630	014v	9	630	015v	0	660	016v	15	630
013v	0	660	014v	0	660	015v	0	690	016v	13	660
013v	0	690	014v	0	690	015v	0	720	016v	16	690
013v	7	720	014v	0	720	015v	0	750	016v	14	720
013v	0	750	014v	0	750	015v	0	780	016v	24	750
017v	13	0	014v	3	780	019v	0	0	016v	10	780
017v	28	30	018v	0	0	019v	0	30	020v	0	0
017v	32	60	018v	0	30	019v	0	60	020v	0	30
017v	17	90	018v	0	60	019v	0	90	020v	2	60
017v	17	120	018v	1	90	019v	0	120	020v	0	90
017v	1	150	018v	0	120	019v	0	150	020v	1	120
017v	22	180	018v	30	150	019v	0	180	020v	1	150
017v	40	210	018v	0	180	019v	0	210	020v	0	180
017v	44	240	018v	0	210	019v	0	240	020v	0	210
017v	24	270	018v	0	240	019v	0	270	020v	0	240

017v	35	300	018v	0	270	019v	0	300	020v	3	270
017v	12	330	018v	0	300	019v	0	330	020v	0	300
017v	6	360	018v	0	330	019v	0	360	020v	6	330
017v	18	390	018v	0	360	019v	0	390	020v	0	360
017v	5	420	018v	0	390	019v	0	420	020v	0	390
017v	22	450	018v	0	420	019v	0	450	020v	0	420
017v	28	480	018v	0	450	019v	0	480	020v	0	450
017v	29	510	018v	0	480	019v	0	510	020v	0	480
017v	15	540	018v	0	510	019v	0	540	020v	0	510
017v	50	570	018v	0	540	019v	0	570	020v	0	540
017v	51	600	018v	0	570	019v	0	600	020v	0	570
017v	55	630	018v	0	600	019v	0	630	020v	0	600
017v	37	660	018v	0	630	019v	0	660	020v	0	630
017v	33	690	018v	0	660	019v	0	690	020v	0	660
017v	35	720	018v	0	690	019v	0	720	020v	0	690
017v	18	750	018v	0	720	019v	0	750	020v	0	720
017v	48	780	018v	0	750	019v	0	780	020v	0	750
017v	26	810	018v	0	780	023v	0	0	020v	0	780
021v	5	0	022v	8	0	023v	73	30	020v	0	810
021v	2	30	022v	3	30	023v	60	60	024v	14	0
021v	5	60	022v	25	60	023v	0	90	024v	6	30
021v	1	90	022v	2	90	023v	78	120	024v	30	60
021v	2	120	022v	28	120	023v	61	150	024v	35	90
021v	2	150	022v	24	150	023v	63	180	024v	12	120
021v	1	180	022v	1	180	023v	74	210	024v	21	150
021v	2	210	022v	5	210	023v	61	240	024v	3	180
021v	11	240	022v	6	240	023v	0	270	024v	0	210
021v	5	270	022v	32	270	023v	63	300	024v	28	240
021v	1	300	022v	5	300	023v	0	330	024v	9	270
021v	6	330	022v	2	330	023v	67	360	024v	7	300
021v	3	360	022v	17	360	023v	5	390	024v	2	330
021v	2	390	022v	25	390	023v	48	420	024v	17	360
021v	8	420	022v	28	420	023v	0	450	024v	15	390
021v	2	450	022v	13	450	023v	65	480	024v	22	420
021v	1	480	022v	6	480	023v	62	510	024v	3	450
021v	3	510	022v	15	510	023v	0	540	024v	0	480
021v	0	540	022v	5	540	023v	1	570	024v	2	510
021v	8	570	022v	6	570	023v	0	600	024v	4	540
021v	9	600	022v	24	600	023v	0	630	024v	1	570
021v	4	630	022v	9	630	023v	0	660	024v	1	600
021v	0	660	022v	3	660	023v	6	690	024v	3	630

021v	0	690	022v	3	690	023v	0	720	024v	20	660
021v	4	720	022v	24	720	023v	60	750	024v	6	690
021v	3	750	022v	0	750	023v	76	780	024v	10	720
021v	1	780	022v	23	780	028v	10	0	024v	39	750
025v	0	0	027v	0	0	028v	0	30	024v	49	780
025v	6	30	027v	1	30	028v	5	60	029v	0	0
025v	0	60	027v	1	60	028v	2	90	029v	0	30
025v	0	90	027v	4	90	028v	0	120	029v	0	60
025v	0	120	027v	0	120	028v	18	150	029v	0	90
025v	0	150	027v	3	150	028v	1	180	029v	0	120
025v	3	180	027v	4	180	028v	1	210	029v	0	150
025v	0	210	027v	0	210	028v	1	240	029v	0	180
025v	0	240	027v	0	240	028v	58	270	029v	0	210
025v	85	270	027v	17	270	028v	22	300	029v	0	240
025v	0	300	027v	0	300	028v	1	330	029v	0	270
025v	0	330	027v	6	330	028v	8	360	029v	0	300
025v	0	360	027v	2	360	028v	1	390	029v	0	330
025v	0	390	027v	1	390	028v	2	420	029v	0	360
025v	0	420	027v	1	420	028v	5	450	029v	0	390
025v	0	450	027v	2	450	028v	8	480	029v	0	420
025v	1	480	027v	1	480	028v	11	510	029v	0	450
025v	0	510	027v	1	510	028v	6	540	029v	0	480
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030v	0	30	031v	1	30	032v	1	60	033v	0	0
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034v	20	750	035v	27	750	036v	16	750	037v	0	720
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038v	0	0	039v	0	0	036v	6	810	037v	0	780
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038v	0	60	039v	0	60	040v	1	30	041v	0	0
038v	0	90	039v	0	90	040v	0	60	041v	0	30
038v	1	120	039v	0	120	040v	0	90	041v	0	60
038v	0	150	039v	1	150	040v	0	120	041v	0	90
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038v	0	210	039v	0	210	040v	1	180	041v	0	150
038v	2	240	039v	3	240	040v	0	210	041v	0	180
038v	0	270	039v	0	270	040v	0	240	041v	0	210
038v	0	300	039v	1	300	040v	1	270	041v	3	240
038v	0	330	039v	0	330	040v	0	300	041v	9	270
038v	2	360	039v	0	360	040v	0	330	041v	2	300
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038v	1	450	039v	1	450	040v	0	420	041v	0	390
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042v	4	240	043v	3	240	044v	2	210	045v	0	180
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062v	0	360	067v	0	360	068v	0	300	069v	0	330
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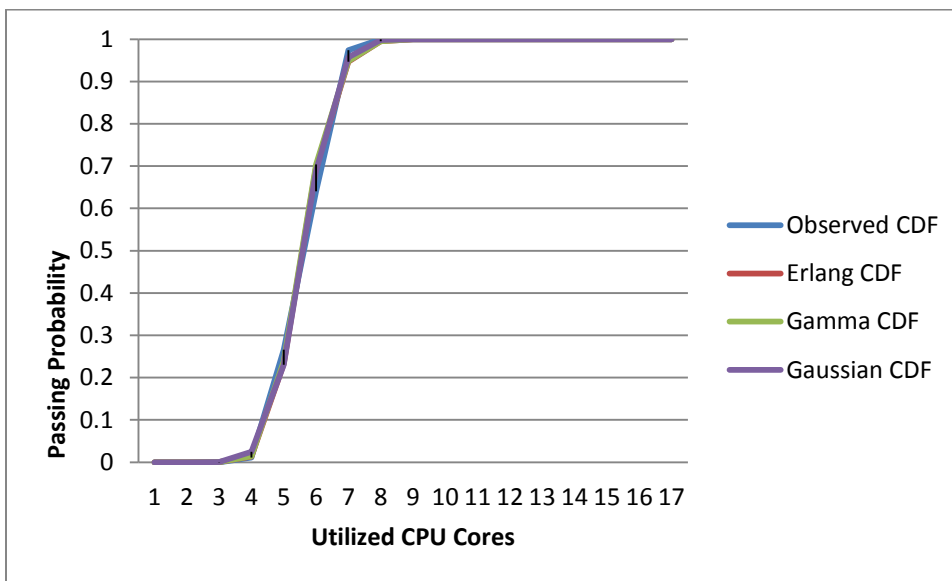
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070v	1	60						
070v	0	90						
070v	0	120						
070v	5	150						
070v	0	180						
070v	0	210						
070v	7	240						
070v	0	270						
070v	1	300						
070v	2	330						
070v	0	360						
070v	2	390						
070v	1	420						
070v	2	450						

070v	1	480
070v	0	510
070v	0	540
070v	0	570
070v	0	600
070v	0	630
070v	0	660
070v	0	690
070v	0	720
070v	0	750
070v	1	780

Appendix C : CDF Tables

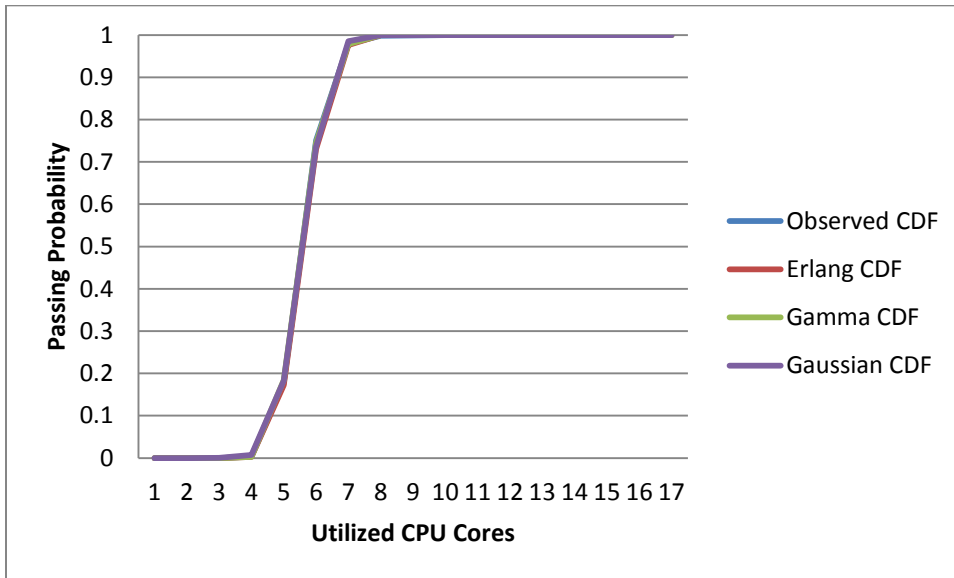
Cumulative Replay Simulation Data

Cores in Use	Observed CDF	Erlang CDF	Gamma CDF	Gaussian CDF
0	0	0	0	0
1	0	0	0	0
2	0	0	0	0.0007
3	0.0112	0.0135	0.0142	0.0247
4	0.2660	0.2328	0.2384	0.2307
5	0.6400	0.6981	0.7041	0.6884
6	0.9740	0.9464	0.9482	0.9572
7	0.9996	0.9952	0.9954	0.9984
8	0.9996	0.9998	0.9998	1
9	0.9996	1	1	1
10	0.9996	1	1	1
11	0.9996	1	1	1
12	0.9996	1	1	1
13	0.9996	1	1	1
14	0.9996	1	1	1
15	1	1	1	1
16	1	1	1	1



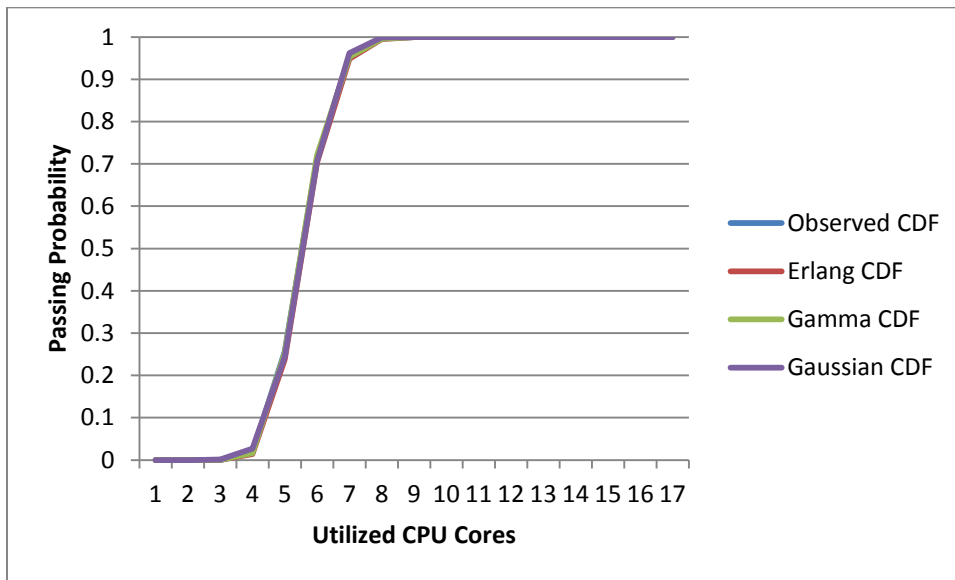
Cumulative App-based Simulation Data

Cores in Use	Observed CDF	Erlang CDF	Gamma CDF	Gaussian CDF
0	0	0	0	0
1	0	0	0	0
2	0	0	0	0.0000
3	0.0033	0.0026	0.0030	0.0073
4	0.1766	0.1718	0.1845	0.1829
5	0.7508	0.7302	0.7455	0.7361
6	0.9791	0.9761	0.9785	0.9849
7	0.9981	0.9993	0.9994	0.9999
8	0.9993	1.0000	1.0000	1
9	0.9998	1	1	1
10	1.0000	1	1	1
11	1.0000	1	1	1
12	1.0000	1	1	1
13	1.0000	1	1	1
14	1.0000	1	1	1
15	1	1	1	1
16	1	1	1	1



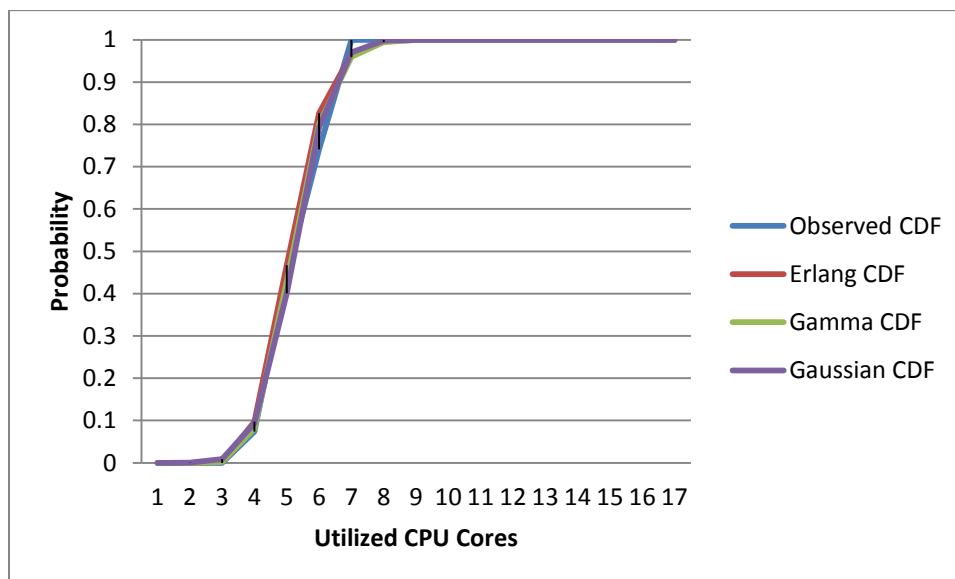
Cumulative Time-based Simulation Data

Cores in Use	Observed CDF	Erlang CDF	Gamma CDF	Gaussian CDF
0	0	0	0	0
1	0	0	0	0
2	0	0	0	0.0008
3	0.0176	0.0140	0.0160	0.0269
4	0.2568	0.2376	0.2533	0.2440
5	0.7139	0.7040	0.7203	0.7059
6	0.9539	0.9484	0.9531	0.9621
7	0.9967	0.9955	0.9960	0.9987
8	0.9996	0.9998	0.9998	1
9	1.0000	1	1	1
10	1.0000	1	1	1
11	1.0000	1	1	1
12	1.0000	1	1	1
13	1.0000	1	1	1
14	1.0000	1	1	1
15	1	1	1	1
16	1	1	1	1



Cumulative Survey Data

Cores in Use	Observed CDF	Erlang CDF	Gamma CDF	Gaussian CDF
0	0	0	0	0
1	0	0	0	0
2	0	0.0023	0.0016	0.0085
3	0.0741	0.0976	0.0809	0.0936
4	0.4444	0.4667	0.4278	0.4007
5	0.7407	0.8262	0.8007	0.7927
6	1	0.9667	0.9593	0.9702
7	1	0.9958	0.9946	0.9984
8	1	0.9996	0.9995	1
9	1	1	1	1
10	1	1	1	1
11	1	1	1	1
12	1	1	1	1
13	1	1	1	1
14	1	1	1	1
15	1	1	1	1
16	1	1	1	1



Vita

Derek Molle was born in Omaha, Nebraska where he lived his early life, graduated from High School in 2006, and graduated from the University of Nebraska Lincoln at Omaha in 2010. While at the University of Nebraska, he began working on a Bachelor of Science in Computer Engineering only to leave the institution four years later with a Bachelor of Science in Electronics Engineering and a wink of knowledge from both fields. After completing the University, Derek was employed by Department of the Air Force as a civil servant.

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14. ABSTRACT The Office of Management and Budget (OMB) has tasked Federal agencies to develop a Data Center Consolidation Plan. Effective planning requires a repeatable method to effectively and efficiently size Air Force Base-level data centers. Review of commercial literature on data center design found emphasis in power efficiency, thermal modeling and cooling, and network speed and availability. The topic of sizing data center processing capacity seems undeveloped. This thesis provides a better, pedigreed solution to the data center sizing problem. By analogy, Erlang's formulae for the probability of blocking and queuing should be applicable to cumulative CPU utilization in a data center. Using survey data collected by 38th Engineering Squadron, a simulation is built and correlation between the observed survey measurements and simulation measurements, and the Erlang, Gamma, and Gaussian-Normal distributions is found. For a sample dataset of 70 servers over 14 hours of observation and a supposed .99999 requirement for traffic to be passed or otherwise unimpeded, Erlang distribution predicts 10 CPU cores are required, Gamma distribution predicts 10 CPU cores are required, Gaussian-Normal distribution predicts 9 CPU cores are required, Erlang B formulae predicts 14 CPU cores are required, and Erlang C formulae predicts 15 CPU cores are required.					
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